Prepared for:

Assessment and Restoration Division
NOAA Office of Response and Restoration
Seattle, Washington 98115

Literature Review

Effects of Oil, Shoreline Treatment, and Physical Disturbance on Sand Beach Habitats

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Prepared: August 2011

Revised Final: August 2015

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1. Introduction

The National Park Service (NPS) and National Oceanic and Atmospheric Administration (NOAA) requested technical support to conduct a literature review on the effects of oil, shoreline treatment, and physical disturbance on sand beach habitats as part of the Natural Resource Damage Assessment (NRDA) being conducted in response to the Deepwater Horizon/ Mississippi Canyon 252 oil spill. The literature review uses current and historical NRDA data and case studies, and published literature (academic and professional sources) to detail the biological communities and physical characteristics of the beaches (from the Florida Panhandle to the central Louisiana Coast/Mississippi River Delta) potentially impacted by the Deepwater Horizon/Mississippi Canyon 252 oil spill. The objectives were to evaluate literature on the potential impacts from chemical contaminants (e.g., oil or dispersant) or physical disturbance (e.g., compaction, desiccation, crushing, removal, or trampling as a result of response), evaluate natural and assisted recovery rates, and identify any missing data or studies (data gap analysis). Direct and indirect impacts may be related to the physical presence of contaminants associated with the spill and/or any physical disturbances to the biological resources or habitat as a result of response efforts. The literature review was not intended to be exhaustive; rather it focused on literature that will provide a high value to the sandy beach injury assessment for the Deepwater Horizon/Mississippi Canyon 252 oil spill.

Four topic areas are included in this literature review:

Topic 1 – Benthic invertebrates: 1) Aquatic and semi-aquatic benthic invertebrates from the shallow littoral to the mean higher high water tide level; 2) Wrack and non-aquatic beach invertebrates

Topic 2 – Potential impacts from oil to sand beach invertebrates

Topic 3 – Potential impacts from response activities to sand beach invertebrates

Topic 4 – Potential impacts from response activities to changes in beach morphology

2. Literature Synthesis Methods

Literature searches were conducted using PubMed, WebOfScience, Google Scholar, and other databases available through EndNote online search tools. Individual citations were re-evaluated to select the articles most relevant to the characterization of beach injury. In all cases, professional judgment was exercised to determine the appropriateness of each article and efforts were made to avoid replication of information generated through similar or related publications and previous literature reviews. The effort was made to specifically narrow the scope of the literature review to literature that provided a high value to the sandy beach injury assessment for the Deepwater Horizon/Mississippi Canyon 252 oil spill. Selected articles and reports were downloaded from online sources, requested from peers, or acquired directly from the RPI in-house library.

Articles selected for each of these topics were summarized in alphabetical order and presented in separate sections within the report. Key words and other sources of information are included in each of these topic sections.

3. EXISTING PHYSICAL RESOURCES

3.1. Geographic Location

Sand beaches affected by the Deepwater Horizon/Mississippi Canyon 252 oil spill extend from Vermilion Parish in western Louisiana to Gulf County in the Florida Panhandle (Fig. 3-1) and vary in degree of exposure to wave and tidal energy and the salinity of adjacent waters. In most cases, the oil stranded on exposed sand beaches on the outer shoreline on barrier islands, barrier spits, and sandy mainland shores, that are adjacent to waters which have little freshwater inputs. There was some oiling of the more sheltered mainland sand beaches along Mississippi Sound, Perdido Bay, and Pensacola Bay, among others, where the adjacent waters can be influenced by freshwater inputs from coastal rivers. There was heavy oiling of the sand spits and bars along several of the Mississippi River passes in Louisiana (e.g., Southwest Pass and South Pass), which are influenced by freshwater discharges. Finally, there was some oiling on sandy habitats on the back side of the barrier islands along Barataria Bay and Timbalier/Terrebonne Bays in Louisiana and Mississippi Sound.

3.2. Habitat Structure

Exposed Gulf sand beach habitats generally consist of the following components, from the highest to the lowest elevations (Fig. 3-2):

- Supratidal Zone – above spring high tides, divided into sub-components
  - Vegetated dunes – Usually dunes are <4 meters (m) in elevation and composed of fine sand. They can range widely in vegetation density and species; the vegetation type and age are good indicators of the time since the last erosional event. There was strict enforcement of best management practices (BMPs) that prohibited entry into or disturbance of vegetated dunes during the response by cleanup workers and equipment.
  - Washover fans – Low areas between dunes where storm waves have overtopped the island and deposited sand in a fan-shaped area on the back side of the island, often into the backbarrier marsh. These habitats often include a lot of shell material, especially on the surface where the shell accumulates as a lag deposit (where the finer-grained sand is removed by wind erosion).
  - Unvegetated backbeach – High, flat surface that is above spring tides but affected by "normal" storm waves that prevent the formation of mature dunes. There may be incipient dunes forming in the lee of wrack deposited during recent storms. Annual vegetation can be present but sparse; perennial vegetation may be taking root in the incipient dunes.
- Beach face – A relatively steep zone between spring high and low tidal levels. It is often divided into three intertidal zones by dividing the tidal range into thirds: upper, middle, and lower beach face. This part of the beach is exposed to daily inundation by the tides and reworking by wave action. Grain size varies from fine- to medium-grained sand. Shell fragments tend to be coarser but minor components of the sediments.
- Low-tide terrace – A gently seaward-sloping surface at the toe of the beach that is composed of fine-grained sand. Often, this terrace is only exposed during spring low tides or meteorological low tide events.

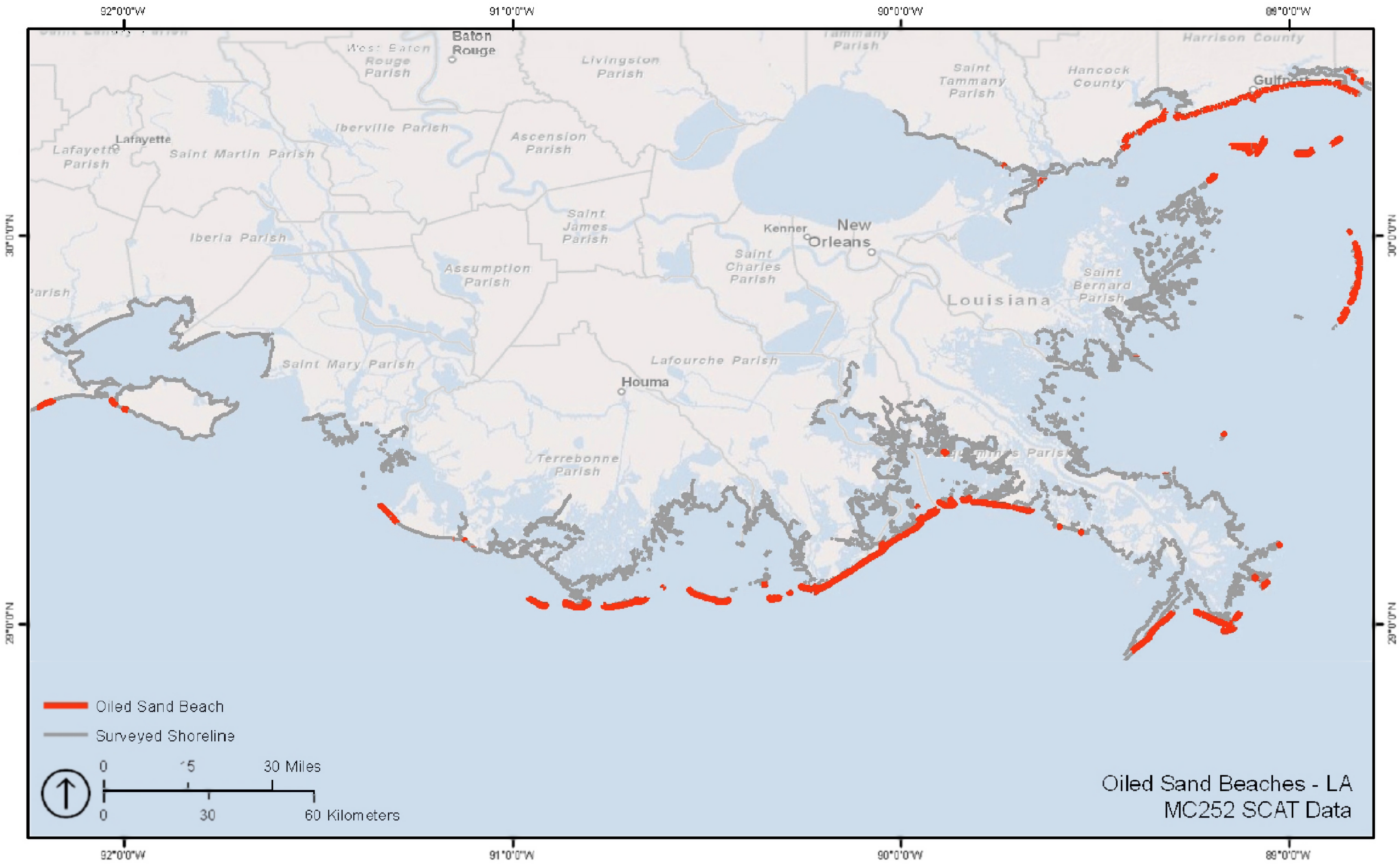

Figure 3-1A. Map of sand substrate habitats that were documented by SCAT as being oiled in Louisiana.

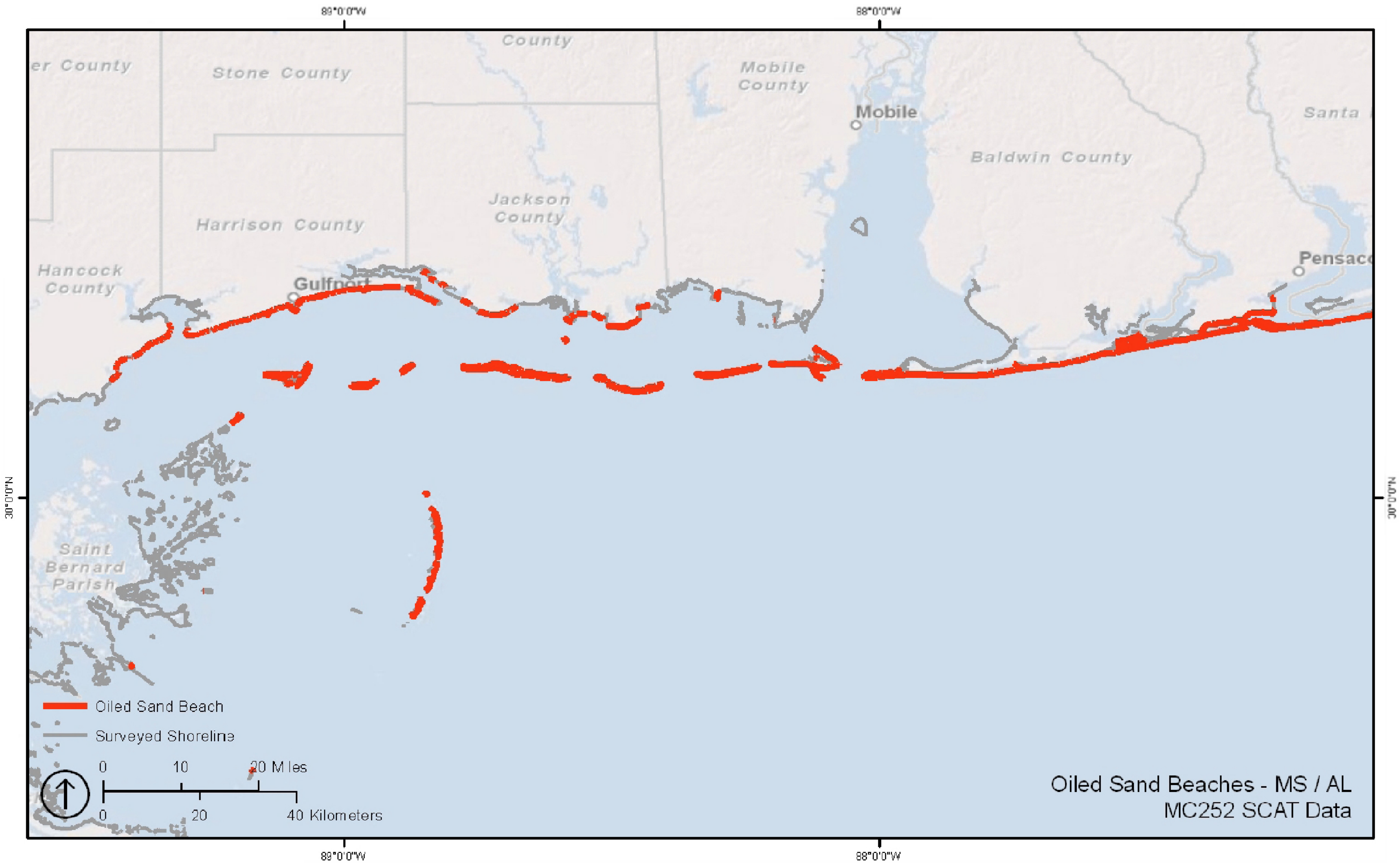

Figure 3-1B. Map of sand substrate habitats that were documented by SCAT as being oiled in Mississippi, Alabama, and western Florida.

Figure 3-1C. Map of sand substrate habitats that were documented by SCAT as being oiled in parts of Florida.

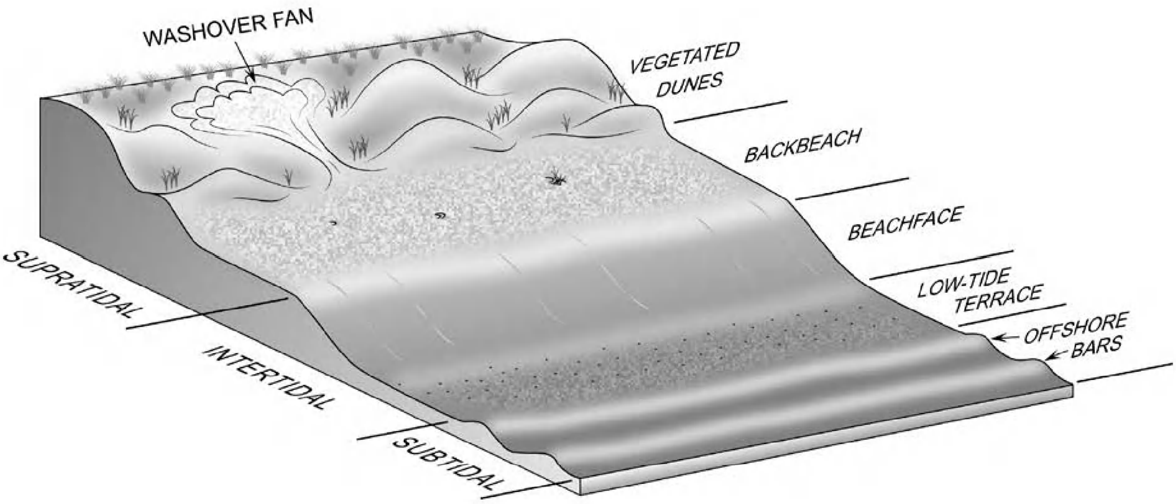

Figure 3-2. Components of sand beaches in the north-central Gulf of Mexico.

- Offshore bars and troughs – Sediment eroded from the beach during storms accumulates in offshore bars that are formed by wave action. The inner bars often migrate onshore after the storm; however, in some settings the offshore bars are stable and migrate very slowly.

However, the morphology of the mainland beaches of Mississippi, bordering Mississippi Sound, is different. These beaches have broad, flat intertidal areas and nearshore sand platforms, with depths typically less than 1.5 m up to 500 m from shore (no published cross-sectional profiles or diagrams were available). These platforms have a well-developed, subtidal bar morphology. According to Schmid (2003b), erosion hotspots on the mainland beaches are correlated with the presence of transverse bars (where they occur at a high angle to the shore).

4. Regional Geology and Geomorphology

4.1. Geophysical Elements

The tidal range in the north-central Gulf of Mexico is microtidal (spring tidal range is < 1 m); as a result, wind-driven waves and associated currents dominant sediment transport processes. There are three general types of wind patterns in the region: 1) the prevailing southeast winds during spring to fall associated with the Bermuda High; 2) tropical cyclones in late summer and fall that generate strong southeast winds as the cyclones approach and cross the shoreline; and 3) cold fronts during the winter generating strong onshore winds that switch to the north as the front passes. Cold front passages are most frequent along the northern Gulf between September and April. These storms are usually associated with extratropical (mid-latitude) cyclones and generate a counter-clockwise rotational wind field. Cold front passages are characterized by pre-frontal southerly winds and post-frontal northerly winds (Roberts et al., 1987). Extratropical cyclones can form in the northwestern Gulf during the winter months. These systems move north and east over the northern Gulf coast and therefore tend to generate a wind field along the coast that is different than the more common extratropical system that moves from west to east and passes to the north. Winds at a given location along the northern Gulf of Mexico with respect to an advancing tropical cyclone are governed by many factors including but not limited to the rate of forward propagation, storm path, the Coriolis force, barometric pressure, and friction of land. Therefore, these systems can generate strong winds out of the northerly quadrant as well as the system approaches the northern Gulf coast. The diurnal land-sea breeze cycle may also be important. From Florida to Louisiana, predominant southeast winds generally generate westerly alongshore currents (Cipriani and Stone, 2001; Georgiou et al., 2005). The counterclockwise circulation of wind associated with passage of tropical cyclones also generates strong westerly currents that result in high-volume, net-westward sediment transport along the Alabama-Mississippi barrier islands (Morton, 2008). In Louisiana, 80% of the waves approach from the southeast, resulting in net sediment transport to the west along most of the barrier islands, with the exceptions of those in the western lee of the Mississippi River delta (from Grand Isle to Bastian Island) and the Chandeleur Islands, where the sediments move both north and south from a nodal point on the south-central portion of the island chain (Georgiou et al., 2005). Along the Florida Panhandle, there is a net sediment transport to the west (Davis, 1994) and multiple sediment sources exist within a cellular, non-integrated, alongshore drift system (Stone et al., 1992). Along the entire north-central Gulf coast, local shoreline configurations, bathymetry, and wind/wave variability produce complex localized alongshore sediment transport directions.

In Louisiana, the mean significant deepwater wave heights vary from a low of 0.75 m off the central coast to a high of 0.95 m off Southwest Pass; nearshore waves are typically less than 0.8 m, with waves up to 1-2 m during extratropical cyclones and cold-front passages (Georgiou et al., 2005). Hurricanes can produce large waves and storm surges; for example Hurricane Katrina's maximum storm surge was 8.5 m at Pass Christian, MS. Tropical cyclones can overwash low barrier islands, transporting sand landward as overwash fans, and sometimes out of the alongshore sediment transport system. Along the Alabama-Mississippi barrier islands, the average significant wave heights are 0.6 m in winter and 0.4 m in summer (Rosati et al., 2007).

Along the low-energy, north-facing sand beaches on the back side of the barrier islands of the northern Gulf of Mexico, cold front passages play a significant role in shoreline morphodynamics and coastal evolution. Subtidal water level changes in adjacent bays and lagoons associated with pre-frontal southerly and post-frontal northerly winds (Roberts et al., 1987) influence the zone of wave energy dissipation across the beach profile and play a significant role in beach and dune responses to storm events. In addition, high frequency, locally generated waves accompanying post-frontal northerly winds entrain and transport sediment and can cause significant erosion along the dune, beach, and nearshore platform (Armbruster et al., 1995). Aeolian processes associated with these weather systems re-work sediments along the north side of the barrier islands and deflate the subaerial portion of the surpratidal zone on the seaward side of the island and the overwash terrace on the landward side of the island (Stone et al., 2004). These fronts can significantly influence sediment transport; in an average year there are 20-30 cold fronts passing through coastal Louisiana (Georgiou et al., 2005).

The sand beaches of the Louisiana barrier islands have average grain sizes in the range of 0.10-0.20 millimeters (mm), which is very fine- to fine-grained sand, although the silt content can be as high as 10-20% (Dingler et al., 1992; Lavoie, 2009; Rosati and Stone, 2009). In contrast, the sand beaches of the barrier islands in Alabama and Mississippi are mostly medium-grained sand (0.29-0.34 mm) and well-sorted (Cipriani and Stone, 2001). The sand beaches along the Florida Panhandle can mostly be characterized as well-sorted, medium-grained sand with a mean of ~0.3 mm (Niedoroda et al., 2004).

4.2. Geomorphology and Long-term Erosion Patterns

The barrier islands, barrier spits, and sandy mainland shores of the north-central Gulf of Mexico (Louisiana to the panhandle of Florida) are highly variable in their origin, morphology, length/width/elevation, frequency of tidal inlets, and long-term erosion history. A barrier island is an elongate, shore-parallel island composed of unconsolidated sediments that is separated from the mainland by wetland environments (Davis, 1994). A barrier spit is similar except that it is connected to the mainland on one end. Sandy mainland shores abut directly against older sand formations, such as along the Caminada Headland, LA and Panama City Beach, FL.

Because of the micro-tidal setting in the north-central Gulf of Mexico, most of the barrier islands and spits are wave dominated, meaning that there are few tidal inlets, small tidal deltas, and numerous washovers. One key exception is the entrance to Mobile Bay, which has a large ebb-tidal delta and complex sediment transport patterns around the mouth of the bay. Also, it is interesting to note that increased tidal prisms resulting from wetland losses inside bays has resulted in the increased efficiency for sediment trapping and an increased aerial extent of ebb-tidal deltas in Louisiana, such as at Pass Abel at the entrance to Barataria Bay (Miner et al., 2009).

In Louisiana, nearly all of the sandy shorelines along the outer coast are undergoing long-term erosion (Fig. 4-1). Rapid rates of relative sea level rise due primarily due to local subsidence and to a lesser degree eustatic (global) sea level rise have caused extensive land loss of the barrier islands fronting Terrebonne, Timbalier, and Barataria Bays through breaching, overwash, and sediment starvation. Large inlets now separate what were once continuous barrier islands or headlands. Recurved spits form on each end, bending into the bay and creating relatively sheltered sandy habitat (that is usually vegetated) on the bay side of the barrier on the ends.

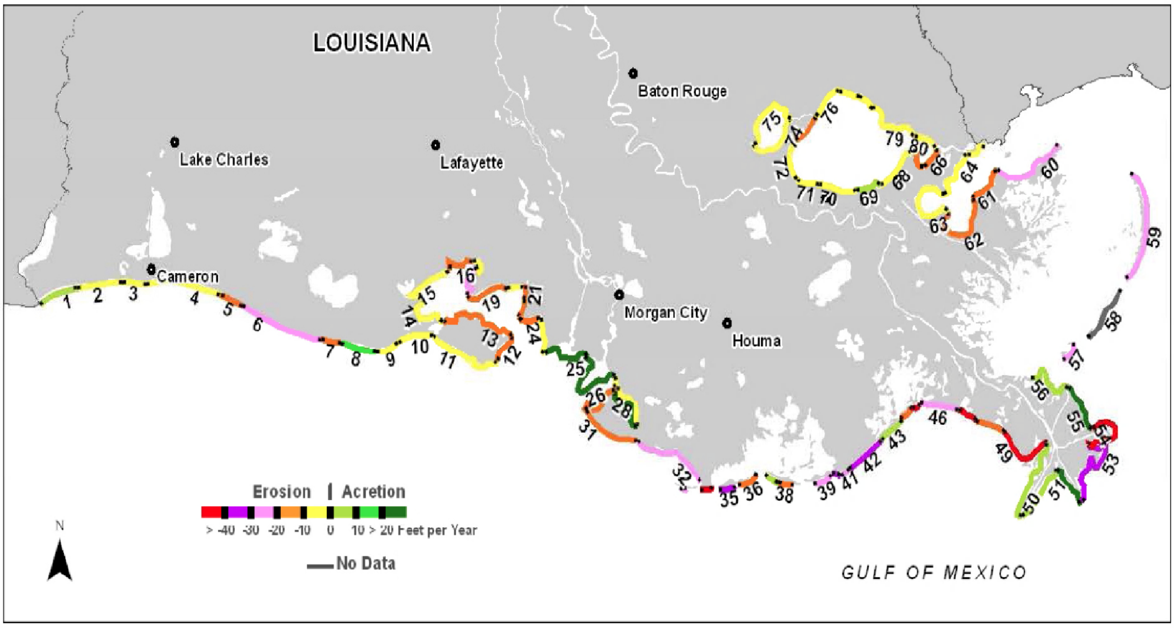

Figure 4-1. Long-term (1904-2005) shoreline changes for coastal Louisiana (Martinez et al., 2009).

The intertidal zone on the outer beaches often includes outcrops of the backbarrier marsh platform at the toe of the beach face, as a cohesive muddy peat with in-place shells and roots on the surface. Restoration projects have been implemented (or planned) along many of the Louisiana barrier islands to close breaches, infuse sediments into the littoral zone, protect existing habitat, restore back-barrier marsh habitats and slow the rate of land loss. Such projects include the direct creation of marsh and dune habitats, beach nourishment, sand fencing, vegetation plantings, and construction of detached, segmented breakwaters (Armbruster 1999, Stone et al. 1999, Underwood et al., 1999).

East of the modern bird-foot delta, the Chandeleur Islands are the transgressive remnants of the late Holocene St. Bernard Delta Lobe of the Mississippi Delta Complex. These islands are highly erosional, as summarized in Lavoie (2009):

> "Of the more than 50 hurricanes that have impacted the Breton National Wildlife Refuge during the past century, 9 were severe. An analysis of shoreline change as a function of hurricane impacts clearly demonstrates that the erosional damage caused by the passage of Hurricane Katrina in 2005 was extremely large when compared with the shoreline erosion that resulted from all of the other hurricane passages during the 20th century. During the 20th century the Chandeleur Islands were characterized by shoreline erosion and island arc rotation due to varying rates of erosion along the shoreline. Between 1922 and 2004, the average rate of erosion was about 35 ft/yr. The amount of erosion due to Hurricane Katrina was an unprecedented 661 ft during the short time period of the hurricane's passage. Simply extrapolating the measured data in a linear fashion with appropriate error bars shows that the islands may persist until about 2064 if there are no future storms of the magnitude of Hurricane Katrina. The islands may, however, become shoals or disappear entirely between 2013 and 2037 if one more Katrina-like storm affects the islands."

The U.S. Geological Survey (USGS) National Assessment of Shoreline Change Project has developed a web mapping application for the Gulf of Mexico that provides a map view of short- and long-term shoreline change evaluations, and historical and modern shorelines (http://coastalmap.marine.usgs.gov/ArcIMS/Website/usa/GoMex/shoreline_change/viewer.htm). Morton (2008) used these data to assess patterns in shoreline change for the AL-MS barriers and identify causal factors. Figures 4-2 through 4-5 show the long-term shoreline changes for these islands.

Mississippi is somewhat unique in that there are two sandy shores–the barrier islands and the mainland shore bordering Mississippi Sound. The barrier islands of the Gulf Island National Seashore (Petit Bois, Horn, and Ship Islands; Figs. 4-2 through 4-4) are very low, with wide inlets, and are generally migrating westward. Additionally, these 3 islands were severely eroded during Hurricane Katrina and have recovered slowly (Morton, 2008). Cat Island has a different orientation and a higher core (Fig. 4-5); therefore, it is eroding in a different pattern and more slowly than the islands to the east. The mainland beaches of Mississippi are very flat, fine-grained, and undergo periodic nourishment.

Schmid (2001a,b; 2003a,b) studied short-term rates of shoreline erosion and beach profile changes along the Gulf Islands National Seashore, including West Ship Island, Cat Island, and East Ship Island.

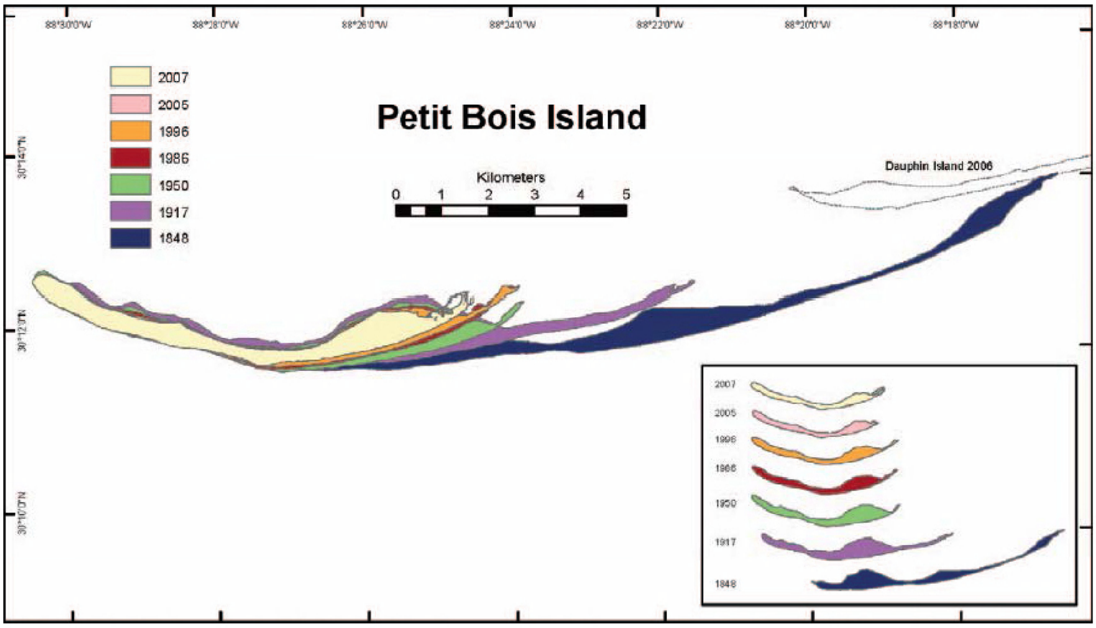

Figure 4-2. Morphological and spatial changes in Petit Bois Island between 1848 and 2007 (from Morton, 2008).

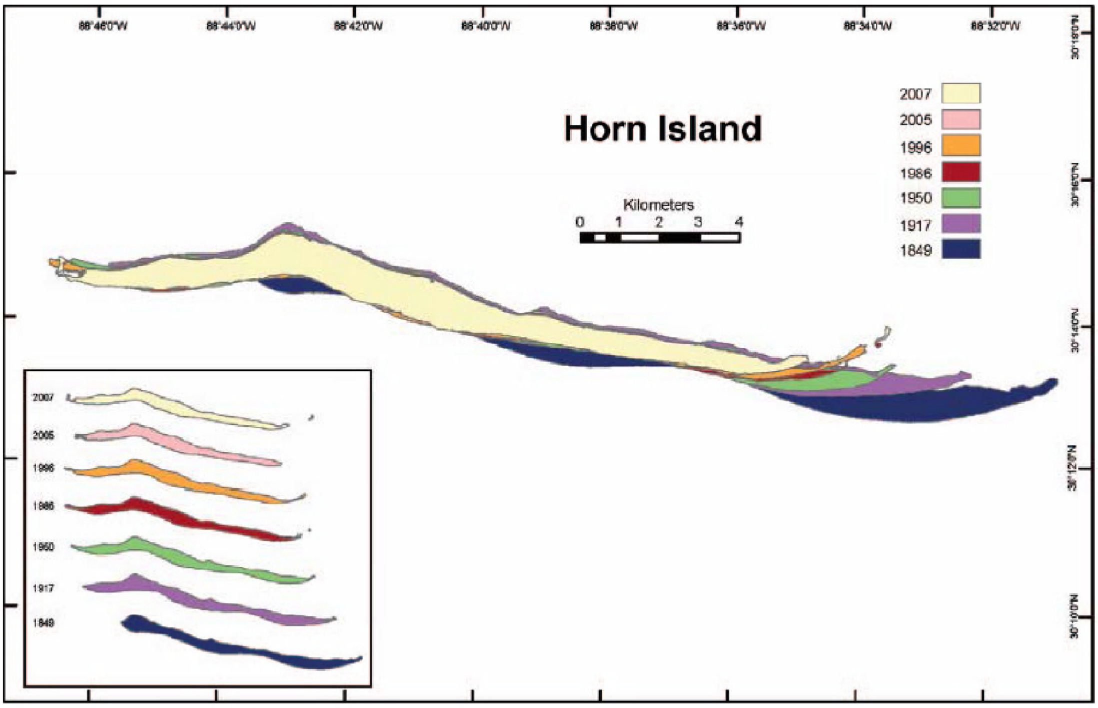

Figure 4-3. Morphological and spatial changes in Horn Island between 1849 and 2007 (from Morton, 2008).

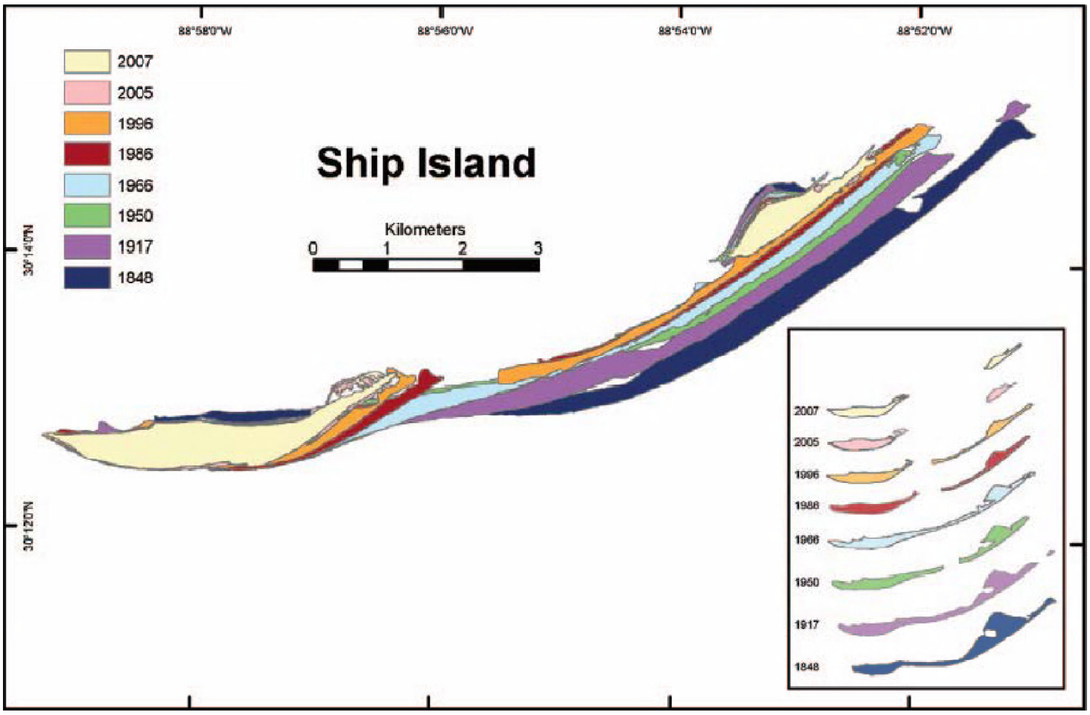

Figure 4-4. Morphological and spatial changes in Ship Island between 1848 and 2007 (from Morton, 2008).

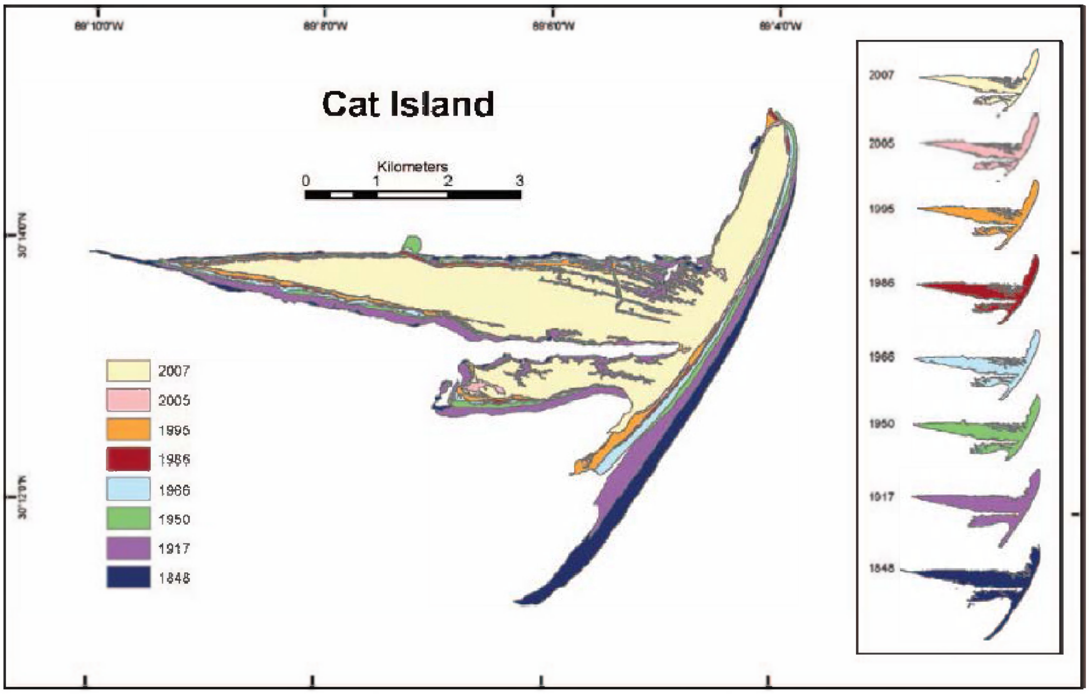

Figure 4-5. Morphological and spatial changes in Cat Island between 1848 and 2007 (from Morton, 2008).

Alabama's sandy shorelines include Dauphin Island (Fig. 4-6). The eastern end of the island is relatively stable; however, the trailing spit on the western end has been breached multiple times by storm channels (Morton, 2008).

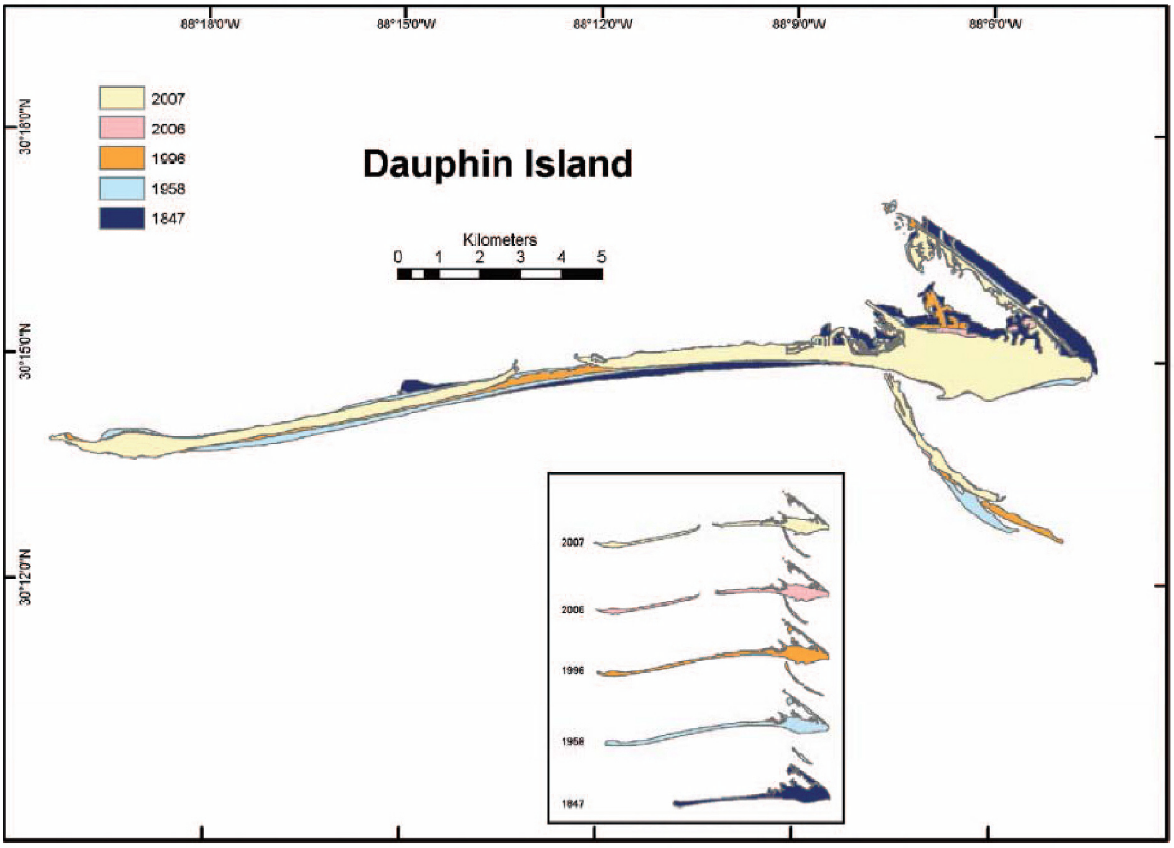

Figure 4-6. Morphological and spatial changes in Dauphin Island between 1847 and 2007 (from Morton, 2008).

The Alabama Department of Conservation and Natural Resources - State Lands, Lands Division, Coastal Section and the Geological Survey of Alabama have a cooperative project, the "Gulf-fronting Shoreline Monitoring Program," to compile historic information and acquire new data to refine the understanding of beach and littoral zone morphological change in response to natural, catastrophic, and engineered processes. Figure 4-7 shows historical erosion rates for the Ft. Morgan Peninsula, one of the products of this project.

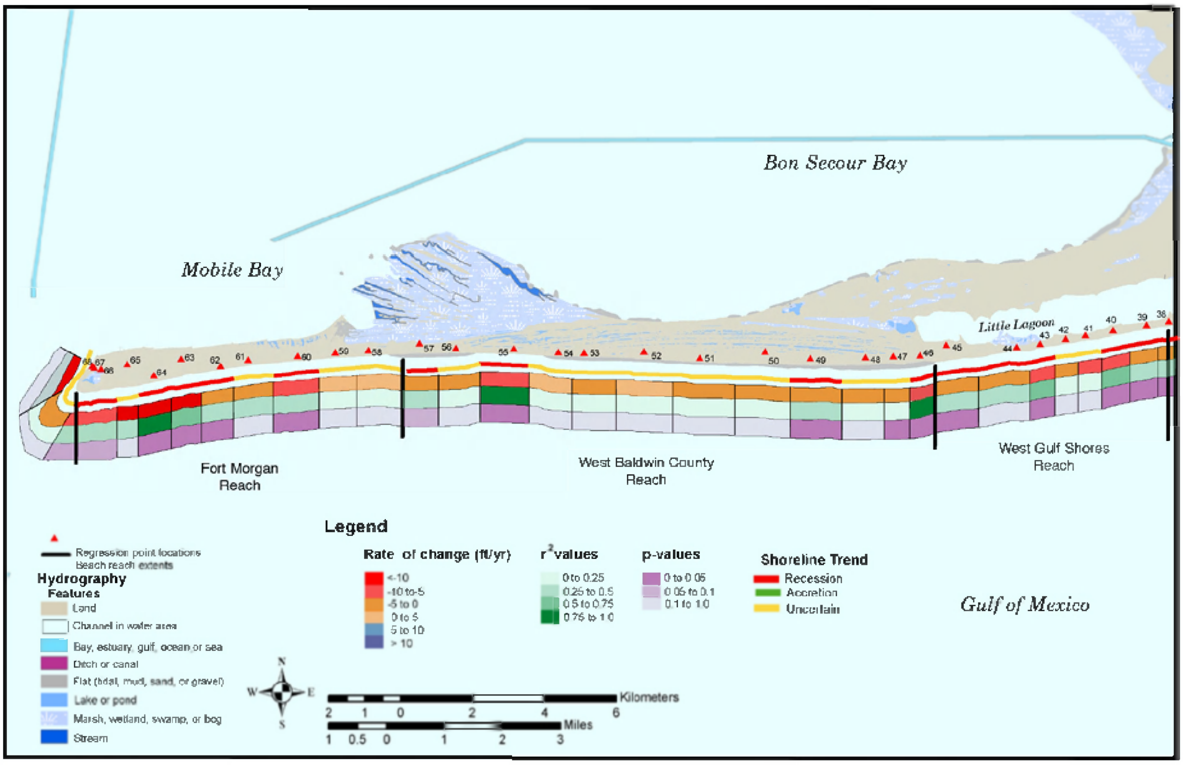

Figure 4-7. Historical erosion rates along the Ft. Morgan Peninsula, part of the Gulf-fronting Shoreline Monitoring Program (Source: http://www.gsa.state.al.us/gsa/coastal/beach.html).

4.3. Cyclic and Seasonal Changes in Beach Profile

Data on short-term changes in beach profiles are usually generated by measuring the cross-shore beach profile at regular intervals along the shoreline, including significant breaks in slope along the beach profile. Recent pre-spill beach profile data for the sand beach habitats affected by the DWH spill are limited in spatial and temporal extent. The Shoreline Cleanup Assessment Technique (SCAT) teams have been measuring beach profiles throughout the impact area, though the start date and frequency of survey varies widely across the impact area. The SCAT program in both Louisiana and the eastern States are in the process of analyzing the profile data and establishing plots showing elevation changes through time. Theses plots will consist of individual profiles, overlays using before and after data of particular storm events, and sweep zones showing the overall active zone and dynamics of the beach. Data will be used to calculate volume changes through time in 2-dimensions and in conjunction with the geographic information used to establish 3-dimensional changes through time. These data may be the best source of documentation of the changes in the beach profile since the spill. Figure 4-8 (Cat Island) and Figure 4-9 (Grand Isle) show representative beach profiles collected by SCAT.

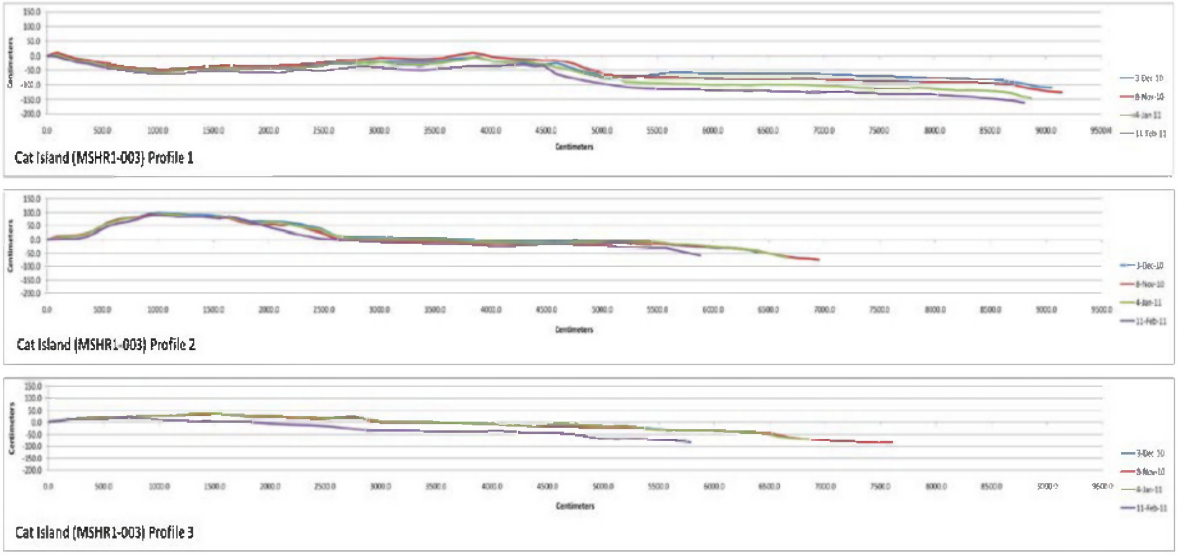

Figure 4-8. Time-series beach profiles at three stations on Cat Island conducted by SCAT teams from December 2010 to February 2011. Note that there has been over 50 centimeters of erosion in the elevation of the intertidal zone over this period. Provided by SCAT as an interim product so unable to revise scales.

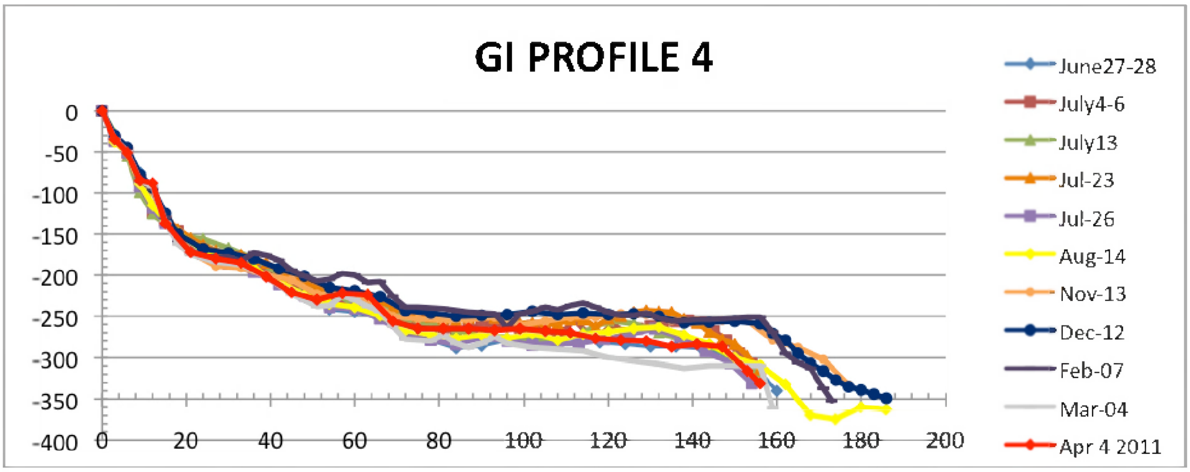

Figure 4-9. Time-series beach profiles at one station on Grand Isle conducted by SCAT teams from June 2010 to April 2011. X-axis is in centimeters; y-axis is in meters. Note that the beach is at about the same position in April 2011 as it was during the first survey in late June 2010, though there had been about 30 m of accretion between June and December 2010. Provided by SCAT as an interim product so unable to revise legends.

In Louisiana, field measurements have documented 20-30 m of coastal erosion during a single 3- to 4-day storm (Williams et al., 1992). The post-storm recovery of the beach can occur very quickly, and is of concern because of the potential for rapid deposition of sediments and burial of newly stranded oil. Grand Isle and Grand Terre III in Louisiana have been nourished; in fact, the restoration project on the eastern end of Grand Terre II was actively pumping sediment onto the island during the spill, resulting in deep burial of oil in some areas.

The State of Florida has a Statewide Coastal Monitoring Program managed by the Bureau of Beaches and Coastal Systems, Department of Environmental Protection, which also has a program to identify those beaches of the state that are critically eroding and to develop and maintain a comprehensive long-term management plan for their restoration. The inventory of critically eroding beaches was updated in June 2010 (FDEP, 2010). Many of the critically eroding beaches have been nourished, including the following beaches in the spill impact area (year of restoration completion):

Pensacola Beach – 2003 Navarre Beach – 2006
Destin – 2007 Western Walton County - 2007
Eglin Air Force Base - 2010 Bay Co. - 2006
Panama City Harbor Dredging with placement in St. Andrews State Park – 2009
St. Andrews State Park – 2009 St. Joseph Peninsula – 2009

Many of the beach nourishment projects include monitoring of the beach to document the project effectiveness. Figure 4-10 is an example of data produced by the beach nourishment monitoring studies that could be used to determine past rates of shoreline change.

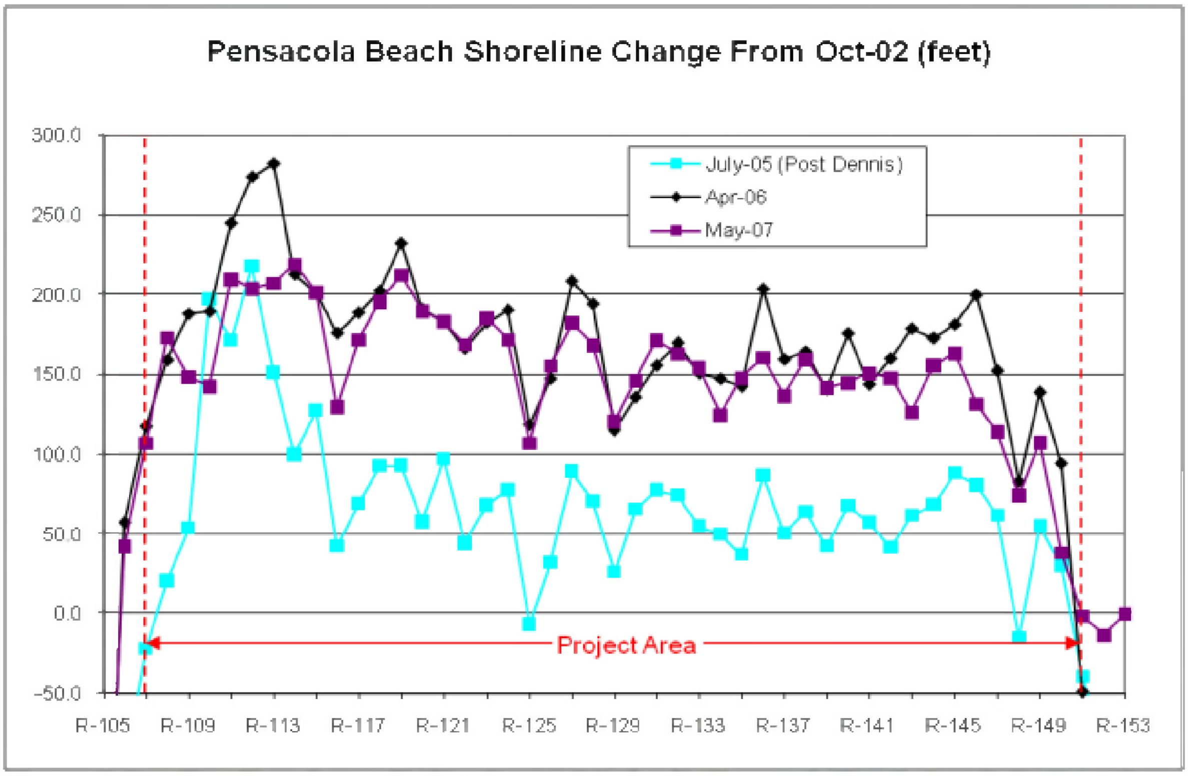

Figure 4-10. Shoreline change (in feet for y-axis) plot for Pensacola Beach (x-axis is the station number along the beach) that was nourished in 2003 (Source: http://beach15.beaches.fsu.edu/Pensacola/shoreline.html). Similar data are available for Panama City Beach, FL.

DWH-AR0259296

4.4. Typical Oil Distribution on Sand Beaches

The oil from the Deepwater Horizon first came ashore on the Chandeleur Islands on 5 May 2010. Over time, the oil stranded on beaches from Vermilion Parish in western Louisiana to Gulf County in the Florida Panhandle, affecting at least 912 kilometers (567 miles) of sand beach habitat. The oil stranded on sand beaches in the following patterns and locations (from landward to seaward); Figure 4-11 shows some of these patterns.

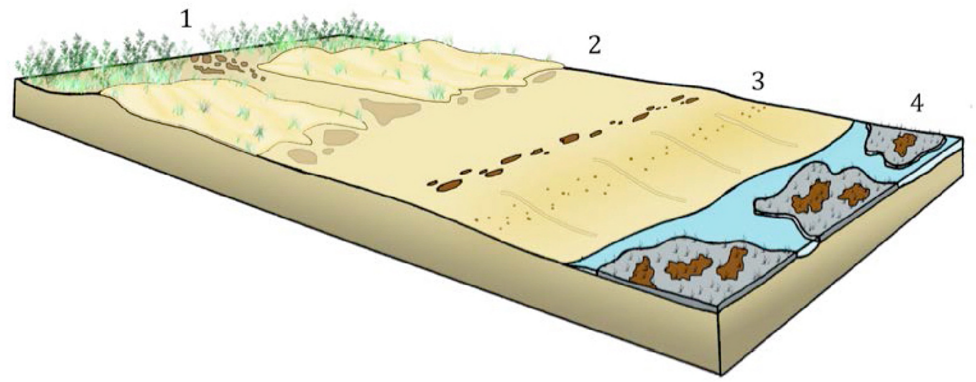

Figure 4-11. The patterns and locations of stranded oil (shown in brown) on sand beaches (modeled after Fourchon Beach in Louisiana). The numbers refer to the numbered bullets in the text: 1) Overwash oiling; 2) Backbeach oiling; 3) Intertidal oiling; 4) Lower intertidal mats; and 5) Submerged oil mats.

1. Overwash oiling – During large storms, such as the high water and wave conditions after the passage of Hurricane Alex in late June 2010, large waves washed over the barrier islands and deposited oil at the distal ends of the washover fans in the low areas between dunes.
2. Backbeach oiling – During the same large 2010 summer storms, oil was deposited on the backbeach, in the supratidal zone, in the form of sporadic to patchy accumulations of surface residues, with concentrations at the base of the dunes and in the berm runnel behind the high-tide berm. In many areas, this oil was covered by clean sand deposited by aeolian processes and/or accretion of the beaches. There is anecdotal evidence that much of the oil was deposited at a time when the beaches were in an erosional condition. Oil continued to strand on the beaches as they accreted between storm events throughout the summer and fall. As a result, the oil became buried up to 1 m deep in the supratidal zone, out of the reach of normal wave erosion of the beach face. Burial to deeper depths has not been documented in any pits, most of which were dug to the water table.
3. Intertidal oiling – Oil in the form of surface residue balls (SRBs) and patties (SRPs) continued to strand on beaches through Spring 2011. The sources of these oil deposits

include lower intertidal surface residue mats, offshore submerged oil mats (SOMs), and buried oil layers in adjacent beaches. The deposition of angular SRBs has been interpreted as indicating a source from the lower intertidal mats and SOMs.

4. Lower intertidal mats – In Louisiana, oil in the form of surface residue mats that were up to 10 centimeters thick in the lower intertidal zone formed under two conditions: 1) mats that were attached to the surface of marsh peat platforms where the oil appeared to be held in place in part by the exposed roots on the peat surface; and 2) mats formed at the toe of the beach, on the low-tide terrace. It is thought that the mats were formed by the accumulation of individual SRBs/SRPs as they were eroded from the beach face. These lower intertidal mats could be up to 100 m in length and 10 m wide. Most of these lower intertidal mats were located and targeted for removal in late summer/early fall when they were exposed during daylight low tides.
5. Submerged oil mats – In the Eastern States, oil in the form of surface residue mats has been found between the toe of the beach and the first bar by "Snorkel SCAT" teams working in wading depth of water. Following the DWH oil spill, subtidal oil mats were formed by: 1) mixing of oil stranded on beaches with sand, followed by redistribution of oil by wave action and deposition at the toe of the beach or in the troughs of offshore bars; or 2) mixing of oil with sand in the surf zone or on offshore bars, followed by deposition onto the bottom forming mats in nearshore and offshore bars. Most of these mats have been removed as of Spring 2011. Operations has developed plans to search for, delineate, and remove SOMs in deeper water farther offshore (as of May 2011).

5. EXISTING BIOLOGICAL RESOURCES

5.1 Introduction

In this section, previous literature on sand beach surveys as well as summary reports are reviewed to identify the dominant biological communities in the intertidal region from the shallow littoral to the mean higher high tide level in the four regions of interest:

1) Florida Panhandle
2) Mississippi/Alabama Barrier Islands: Horn Island, Petit Bois Island, Ship Island (MS); Dauphin Island (AL)
3) Chandeleur Islands (LA)
4) Central Louisiana Coast (from the Mississippi Delta west to Raccoon Island)

Table 5-1 lists the species that are commonly found in these locations.

The majority of the data presented in this section was collected from peer-reviewed journal articles, with some information provided by reports prepared by the National Park Service, Minerals Management Service, NOAA, and the Florida Fish and Wildlife Conservation Commission (Florida FWC). Efforts were initially limited to region-specific studies; however, the lack of sand beach macroinvertebrate studies in the northern Gulf of Mexico (GOM) initiated a broader search that included both Atlantic and Pacific coasts, South America (mainly Brazil), as well as studies conducted overseas (Spain, Italy, Sweden, Norway, and Australia). Additional information was provided through correspondence with local resource experts (T. Black and K. Smith, Florida FWC; C. Pomory, University of West Florida).

Search words and word combinations include: sand beach macroinvertebrates, sand beach infauna, epifauna, intertidal macrofauna, all genus/species and common names listed in Table 5-1, Gulf of Mexico, wrack, stranded wrack, stranded wrack macrofauna, and stranded wrack invertebrates.

Table 5-1. Dominant sand beach macrofauna of the intertidal zone recorded in the four regions of interest for the Shoreline Sand Beach TWG. Texas and the broader northern GOM were also included due to a lack of available data at the specific sites.

Species	Location Based on Reviewed Literature	Source*
Emerita talpoida (mole crab)	FL, AL/MS, Chandeleur Islands (LA)	1, 4, 12
Emerita spp.	Bird's Foot (LA), northern GOM, TX	13
Donax variabilis (coquina clam)	FL, AL/MS, LA, Chandeleur Islands (LA)	1, 4, 12, 23
Donax spp.	Bird's Foot (LA), TX, northern GOM	13, 19
Ocypode quadrata (ghost crab)	FL, AL/MS, northern GOM	2, 14, 13
Arenicola cristata (lugworm polychaetes)	FL	1
Haustoriid amphipods	FL, AL/MS, TX, northern GOM	1, 5, 10, 13
Ancinus depressus (isopod)	FL	1
Scolelepis squamata (polychaete)	FL, AL/MS, TX, northern GOM	1, 4, 5, 13
Limulus polyphemus (horseshoe crab)	FL	7
Dispio uncinata (polychaete)	MS/AL	10
Callichirus islagrande (ghost shrimp)	Chandeleur Islands (LA), Bird's Foot (LA), northern GOM	3, 12, 13
Orchestia grillus (talitrid amphipod/semi-terrestrial)	TX	5
Order Diptera (fly larvae)	TX	5
Order Coleoptera (Bledius spp., rove beetle)	TX	5
Order Collembola (springtail)	TX	5
Order Hemiptera (nymphs)	TX	5
Streblospio benedicti (polychaete)	TX	5

* See reference section for details.

5.2. Sand-Associated Species

Sand beaches are often regarded as less biologically valuable than other more structurally complex habitats (rocky shores or mangroves). Although they may not possess the same level of biodiversity and biomass of adjacent habitats (such as nearshore tidal flats), these habitats play clear functional and ecological roles (see Defeo et al., 2009). Sand beaches are dynamic habitats constantly reworked by physical forces and disturbances (waves, tides, and storm dynamics), and inhabited by a complex and specialized biotic assemblage. Invertebrate communities on intertidal sand beaches are often dominated by a handful of species, which contribute significantly to the overall energy budget of these habitats. These areas provide habitats for diverse ecologically functional fauna ranging from interstitial primary producers and decomposers (bacteria, protozoans, microalgae), to small and large secondary producers (meiofauna–organisms retained by a 100 µm mesh sieve; and macrofauna–organisms retained by 1 mm mesh sieve). The actively burrowing invertebrates (crustaceans, mollusks and polychaetes) that inhabit sand beaches and the continuous supply of wrack supports a rich supralittoral fauna of crustaceans and insects.

The meiofauna assemblage inhabits interstitial sand pores near the surface of the beach, and is numerically dominant by nematodes and harpacticoid copepods. Other members of this assemblage include gastrotrichs, oligochaetes, ostracods and turbellarians, while non-permanent member include larvae and juveniles of macrofauna species (McLachlan, 1983; McIntyre, 1969). Their spatial distribution is largely controlled by grain size, temperature, salinity, moisture content, redox potential, and organic input (McLachlan, 1983; McIntyre, 1969), and their cyclic migrations are associated with tidal and diurnal cycles, and seasons (McLachlan, 1983). On exposed beaches, meiofaunal densities are in the order of 10^6 individuals/m^2, and dry biomass ranging from 20-4400 mg/m^2 (see McLachlan, 1983). These members of the benthic community are short lived (egg to egg production of weeks to a few months), have high reproductive rates (2–4 generations per year), and play an important role in the nutrient cycling within the interstitial environment (McLachlan, 1983; McIntyre, 1969). Although the numerical abundance of meiofauna exceeds that of the macrofauna (average ratio: 10^5 to 1), their biomass is much lower than that of the macrofauna (average ratio: 1: 5) (McLachlan, 1985). However, these groups appear to play distinct roles within these habitats, as little energy exchange exists between them (see McLachlan, 1983).

By contrast, the macrofauna assemblage is comprised of bivalve mollusks, decapods crustaceans, polychaete, amphipods, and isopods, which concentrate at the sand surface of the intertidal and surf zones. Crustaceans tend to dominate exposed beaches, polychaetes sheltered beaches, and mollusks intermediate exposure gradients (see McLachlan, 1983). The spatial distribution of the macrobenthos is influenced by several factors, including sand grain size, moisture and organic content, beach slope, waver action and large disturbance events (e.g., storms) (see McLachlan, 1983). Sand beach macrofauna are highly mobile, with movements influenced by tides, lunar and seasonal cycles, and life stages (McLachlan, 1983). Although dry biomass is highly variable across beach types, it tends to increase with wave exposure with very exposed dissipative beaches having some of the highest biomass values (McLachlan, 1983; McLachlan et al. 1996).

Although not well studied in this region, benthic invertebrates are an important part of the sand beach environment. Benthic invertebrate studies on sand beaches focus primarily on macrofauna rather than meiofauna. Therefore, this review discusses only important aspects of the macrofauna community on beaches of the Gulf of Mexico. Only in the absence of region-specific information, literature from other areas is considered.

5.2.1 Ecological Services and Community Structure

Macroinvertebrates provide a wide variety of ecological services and functions. Many invertebrates use the nutrition from particulates and detritus brought in on tides and waves consuming organic matter and recycling nutrients that otherwise would become trapped in the sediments. Amphipods, crabs, and insects convert the energy content of stranded wrack washed onto the beach into forms available for larger animals, including shorebirds, surf zone fish, and other higher trophic level aquatic organisms. The transfer of energy from lower trophic levels (e.g., amphipods, polychaetes) to higher trophic levels (e.g., fish, birds) can be reduced after contamination of sediments occurs and (temporarily) when contaminated sediments are removed and replaced with clean material through beach nourishment. Some macroinvertebrates are sensitive to external environmental stress (e.g., beach restoration projects, oil/chemical pollution); and, therefore, are an integral part of the study of the injury to sand beaches.

Although there are several zonation schemes (see Defeo and McLachlan, 2005), the literature typically divides the intertidal zone of exposed sand beaches into three zone boundaries based on physical variables (e.g., sediment grade, beach slope, wave action, duration of inundation) (Filho et al., 2009; McLachlan, 1983; Nelson, 1993; Peterson et al., 2000; Shelton and Robertson, 1981). These zones include a dry sand or substrate of the upper intertidal at or above the drift line dominated by air breathers, the damp substrate of the middle intertidal, and the wet sand of the lower intertidal or swash zone, both dominated by marine water breathers (see Defeo and McLachlan, 2005; Figure 5-1). A distinct across-shore faunal zonation is apparent along the intertidal zone as a result of biotic (morphological, behavioral, and adaptive characteristics) and abiotic factors (grain size, sediment moisture, wave exposure) (McLachlan, 1983; McLachlan et al., 1996; Filho et al., 2009). Aside from community level zonation patterns, some species also exhibit class size zonation along the intertidal zone possibly due to differences in suitable conditions specific for each life stage (McLachlan, 1983; McLachlan et al., 1996). It is important to note that the zone boundaries mentioned above are not static in space and time, and that therefore, there is substantial overlap in species composition across these zones.

In the northern GOM, the upper intertidal zone is typically dominated by talitrid amphipods, ghost crabs, Haustoriid amphipods, and isopods (Nelson, 1993). These invertebrates are often associated with macrophyte wrack stranded along the upper intertidal zone and provide food and habitat for many sand beach macrofauna (Figure 5-1). The swash or surf zone is dominated by *Donax* (coquina clams), *Emerita* (mole crabs), polychaetes, Haustoriid amphipods, and burrowing ghost shrimp (*Callichirus islagrande*) (Dahl, 1952; Nelson, 1993), varying in their dominance with geography, seasonality, and beach characteristics (exposed vs. protected) (Rakocinski et al., 1998a). The middle intertidal is a combination of the upper and lower intertidal invertebrates (e.g., isopods, amphipods, polychaetes) that move up and down with the tides or scavenge across the beach based on prey availability. Table 5-2 provides available life history data for the dominant sand beach macrofauna of the northern GOM. Community metrics (e.g., abundance, density, and biomass) for each species are shown in Table 5-3, when data were available. These data were collected from studies conducted primarily in the GOM, but information on the order, genus, or species with studies outside the region of interest is also provided.

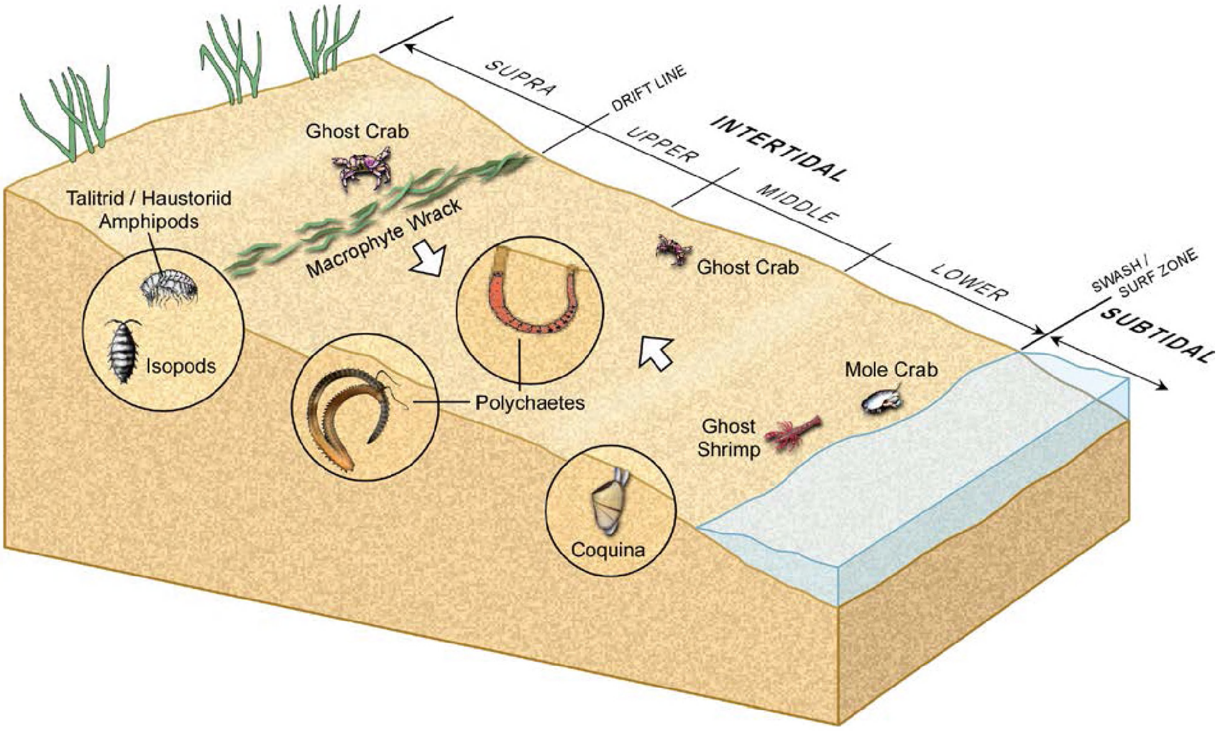

Figure 5-1. Distribution of representative sand beach invertebrates within the supratidal and intertidal zone. The three zones of the intertidal zone grade into each other and are not necessarily rigid in their extent. The fauna typical of the middle intertidal zone is a combination of those found on the upper and lower intertidal zones.

Wave energy and substrate grain size are the two dominant factors that control the community structure on exposed sand beaches (Shelton and Robertson, 1981; Rakocinski et al., 1991). Diversity of macrofauna is greatest downshore and decreases on the mid to upper shore. Wave exposure plays a major role in the diversity of sand beach communities with higher energy beaches generally reporting lower density and diversity (Nelson, 1993). However, McLachlan (1983) found that slope and grain size influenced community diversity. Flat exposed beaches with heavy wave action and fine sediments supported a higher diversity than steep beaches with coarse sediments. Nelson (1993) indicated that the key factor influencing diversity, as well as abundance and biomass values, on exposed beaches is whether the beach is reflective (steep and narrow) or dissipative (wide and flat). On sand beaches, total abundance and biomass increase exponentially with flatter beach slope, finer-grained sand, larger tides (for abundance), and higher wave energy (for biomass) (McLachlan and Brown, 2006). Wide, sloping beaches, as are found along the Texas coastline, tend to dissipate wave energy evenly over the intertidal zone that may allow for a more suitable environment for animals such as filter feeders (Nelson, 1993). Shelton and Robertson (1981) found that density and biomass were greater on a Texas barrier island beach that was characterized with greater wave energy and more uniformly well-sorted sand than a nearby mainland beach. Diversity and richness, however, were higher on the mainland beach. Very exposed, dissipative beaches have some of the highest biomass values recorded when compared to other beach classifications (McLachlan and Brown, 2006).

Table 5-2. Life history data from reviewed literature on the dominant fauna of the intertidal zone in sand beach locations impacted by the Deepwater Horizon oil spill for sand- and wrack-associated species. Superscript indicates the original source (see reference section for details). Only in the absence of region specific literature, studies from other regions are used. In brackets, information from a related species. NA: Not Available.

Species	Life Span	Burrowing Depth	Temporal Distribution	Timing of Reproduction and Recruitment	Reproductive Strategy	Life Stage Assoc with Substrate	Spatial Distribution
SAND-ASSOCIATED SPECIES							
Emerita talpoida (mole crab)	1-2 yrs[13]	NC: < 5 cm[27]	MS/AL, FL: dominant in spring and autumn[10]; Sand Key, FL (near Tampa): peaked in summer and fall (Jul-Nov)[16]	Eggs produced in spring[26]; females carry eggs during summer months[13]; FL: release larvae -June/July and September/October; peak recruitment in fall[16]	Planktonic larvae[9]	NC: eggs, juveniles, adults[21]	Swash zone[9]
Arenicola cristata (lugworm polychaetes)	[*A. marina*: 5-6 years][39]	MA: 6-8 in	TX: peaked in May and July[5]	FL: spring[A]	SC: planktonic larvae[25]	Larvae, juveniles, adults[25]	Swash zone[1]
Ocypode quadrata (ghost crab)	2-3 yrs[26]	Occasional burrower; no more than 1 m[13]	Active Mar-Dec; dormant in winter within a sand-sealed burrow[13]	Reproduce in summer months; juveniles appear in Jul and late Oct[13]	Planktonic larvae[13]	Juveniles, adults[24]	Backshore and upper intertidal[2]; juveniles: foreshore behind surf zone; adults: sandy backshore[13]

Table 5-2. Continued.

Species	Life Span	Burrowing Depth	Temporal Distribution	Timing of Reproduction and Recruitment	Reproductive Strategy	Life Stage Assoc with Substrate	Spatial Distribution
Donax variabilis (coquina clam)	1 yr[26]; SC study: 1-2 yrs[22]	[*D. trunculus*: 0-2 m][41]	FL: max densities in summer months[1]; Sand Key, FL: peak abundance in Oct-Nov and Apr[16]; Texas: peak in spring and summer; lowest densities in fall/winter[13]	NE FL: spawn and recruit all yr[16]; GOM: reproduce in spring and summer; recruitment in May and Oct[26]	Planktonic larvae[9]	Eggs, juveniles, adults[22]	Swash zone[1]; patchy[22]
Haustoriid spp. (amphipod)	GA: 1.5 yr[38]	TX: 5-12 cm[5]	FL: peak abundance in spring and summer; min abundance in late fall[1]	GA: highest female fecundity in spring-summer[38]	Broods[11]	Eggs, juveniles, adults	Swash zone and first sand bar[1]; patchy[5]
Ancinus depressus (isopod)	[*Tylos europaeus*: 3-6 yr][42]	NA	FL: peak abundance in late spring and summer; min abundance in late fall to May[1]	[*Tylos europaeus*: spring-summer][42]	Broods	Eggs, juveniles, adults	Low to high intertidal zone
Scolelepis squamata (polychaete)	Brazil: 0.49-0.66 yrs[28]	40 cm[see 43]	FL: density increases in Feb-Jun[16]; MS: high in winter and spring[10]; TX: lower densities in May and June; peaks in Jul[5]	Brazil: recruitment in April and Oct; ovigerous females present all yr.[28]	Broadcast spawners[44]; Benthic larvae[9]	Eggs, larvae, juveniles, adults	Mid tide to swash zone[9]
Limulus polyphemus (horseshoe crab)	Atlantic coast: 14-19 yrs[29]	Eggs: 5-30 cm	Year round (less in Dec-Feb)[7]	Feb-Nov[7]	Planktonic larvae	Eggs, adults	Subtidal/surf
Dispio uncinata (polychaete)	[Spionidae: 1.8±0.7 yrs][40]	NA	Dominant: fall; abundant summer and fall[10]	NA	Broadcast spawners and pelagic larvae[44]	Juveniles, adults	Low tide[36]

Table 5-2. Continued.

Species	Life Span	Burrowing Depth	Temporal Distribution	Timing of Reproduction and Recruitment	Reproductive Strategy	Life Stage Assoc with Substrate	Spatial Distribution
Streblospio benedicti (polychaete)	[Spionidae: 1.8±0.7 yrs][40]	NA	Lower densities in May and June[5]	NA	Broods and planktonic larvae[44]	Juveniles, adults	Low to high intertidal
Callichirus islagrande (ghost shrimp)	Callianassids: 2-4 yrs[30]	1-2m[6]; 30-50 cm[8]; >100 cm[2]; > 1 m[13]	MS/AL/FL: Higher densities in fall and winter[10]	Breeding season: spring to fall[20]; recruitment occurs 2x per yr (juveniles appeared in Jul, Jan, and Sep); gravid females collected in May, June, Jul, and Sept.[8]	Planktonic larvae	Larvae, juveniles, adults	Low to high intertidal; barrier islands[3]; patchy[13]
WRACK-ASSOCIATED SPECIES							
Orchestia grillus (talitrid amphipod/ semi-terrestrial)	[*Tylos europaeus*: 3-6 yr][42]	NA	Low density and biomass in May-Jun; peaked from Jun-Aug[5]	NA	Brood #s = 10-50, rarely exceeding 100[24]; broods[24]	All stages[24]	Patchy[23]
Haustoriid spp. (amphipod)	GA: 1.5 yr[38]	TX: 5-12 cm[5]	FL: peak abundance in spring and sum; min abundance in late fall[1]	NA	Broods[11]	Larvae, juveniles, adults	Patchy[5]
Insects[B]	NA	NA	Abundance peaked in Jun; Density and biomass peaked in Jun and Aug[5]	NA	NA	Diptera larvae, Hemiptera nymphs[5]	Patchy[5]

[A] http://www.sms.si.edu/irlspec/Arenic_crista.htm; [B] Including the orders Diptera (flies), Coleoptera (ex: *Bledius* spp., Rove Beetle), Collembola (springtail), and Hemiptera (nymphs)

Table 5-3. Metrics from dominant fauna of sand and stranded wrack habitats in the northern GOM. The values presented here are maximum values, or ranges recorded at a site or sites within a study. These values may not be representative of a site or area as ranges only represent samples where the species was found.

Species	A: Relative Abundance (%) D: Density (No./m^2 ; noted otherwise) B: Biomass (dry weight; g/m^2; noted otherwise)	Location	Source/Notes*
SAND-ASSOCIATED SPECIES			
Emerita talpoida (mole crab)	**D:** 137-159	NC	17; indicator species in FL
	D: 45 (8-6,608)	Gulf Islands National Seashore	45
Ocypode quadrata (ghost crab)	**D:** *O. cordimama*: 0.485 (supratidal); 2.11 (foredune)	Australia	15; indicator species in FL
	D: 0.02-0.13	NC	34
	D: 0.08 **B:** 0.007	TX (barrier island-Malaquite)	32
Donax variabilis (coquina clam)	**D:** 185,248/ m3	Sand Key, FL	16; Indicator species in FL
	D: 72-13,114	Sanibel Island, FL	16
	D: 264-334	NC	17
	D: *Donax* spp.: 100 clumps per mi; 1000s indiv per clump	GOM	13
	D: Donax spp.: 22-6,542	TX	19
	D: 10,000	TX	23
	A: *Donax* spp: 21.9 **D:** 871 **B:** 23 (wet weight)	TX (barrier island-Malaquite)	32
	A: *Donax* spp: 16.6 **D:** 233 **B:** 3.5 (wet weight)	TX (mainland- McFaddin)	32
	B: 6.45 kj/m2 (transect); 67.2 kj/m2 (max)	SC	22
	D: 62 (8-1,272)	Gulf Islands National Seashore	45
Haustoriid spp. (amphipod)	**D:** 22-5,017	TX	19
	A: 30.3 **D:** 423 **B:** 0.37 (wet weight)	TX (mainland- McFaddin)	32

Table 5-3. Continued.

Species	A: Relative Abundance (%) D: Density (No./m^2 ; noted otherwise) B: Biomass (dry weight; g/m^2; noted otherwise)	Location	Source/Notes*
	A:66.1 **D:** 2,627 **B:** 3.6 (wet weight)	TX (barrier island-Malaquite)	32
	D: *Haustorius jayneae*: 192 (8-13,592)	Gulf Islands National Seashore	45
Ancinus depressus (isopod)	**D:** 16 **B:** 0.06 (wet weight)	TX (mainland- McFaddin)	32
	D: 6 **B:** 0.003 (wet weight)	TX (barrier island-Malaquite)	32
	D: 102.6 **B:** 0.204	Panama - Pacific coast	35
	D: 80.3 **B:** 0.194	Panama - Atlantic coast	35
	D: 50 (8-760)	Gulf Islands National Seashore	45
Scolelepis squamata (polychaete)	**A:** 86.1 **D:** 56 **B:** 0.21	Spain	18; 13: best indicator species of a clean sandy swash zone
	D: 22-1,658	TX	19
	A: 41.4 **D:** 579 **B:** 0.45 (wet weight)	TX (mainland- McFaddin)	32
	A: 7.7 **D:** 307 **B:** 0.33 (wet weight)	TX (barrier island-Malaquite)	32
	D: 350	Brazil	36
	D: 20,277	Brazil	28
	D: 142 (8-3,536)	Gulf Islands National Seashore	45
Limulus polyphemus (horseshoe crab)	**D:** 500-1000 ind per single spawning event	FL	7
	D: 8	Gulf Islands National Seashore	45
Dispio uncinata (polychaete)	**D:** 1.63 **B:** 0.004 (wet weight)	TX (mainland- McFaddin)	32
	D: 1.81 **B:** 0.01 (wet weight)	TX (barrier island-Malaquite)	32

Table 5-3. Continued.

Species	A: Relative Abundance (%) D: Density (No./m^2 ; noted otherwise) B: Biomass (dry weight; g/m^2; noted otherwise)	Location	Source/Notes*
	D: 150	Brazil	36
	D: 36 (8-160)	Gulf Islands National Seashore	45
Callichirus islagrande (ghost shrimp)	**D:** 4-90 **B:** 270 (wet weight); 70 (dry weight)	LA	8
	D: 30-100	LA	6
	D: 0.08 **B:** 0.02 (wet weight)	TX (barrier island-Malaquite)	32
	D: Several burrows	GOM	13
	D: 30 (8-448)	Gulf Islands National Seashore	45
WRACK-ASSOCIATED SPECIES			
Orchestia grillus (talitrid amphipod/semi-terrestrial)	**A:** 1.7 **D:** 0-600 **B:** 0-0.4	TX	5
	D:Megalorchestia spp: 85-10,200/m **B:** Megalorchestia spp: 1-378 g/m	CA	31
Haustoriid spp. (amphipod)	**A:** 77.2 **D:** 0-16,000 **B:** 0-3.75	TX	5
Order Diptera (fly larvae)	**A:** 66.1 **D:** 4.88	Spain	18
	A: 3.3 (of wrack insects)	TX	5
Order Coleoptera (ex: Bledius spp., Rove Beetle)	**A:** 62.7 (of wrack insects)	TX	5
	D: 50-100	Brazil	36
	D: 51-5,160/m	CA	31
Order Collembola	**A:** 26.9 (of wrack insects)	TX	5
Order Hemiptera (nymphs)	**A:** 7.1 (of wrack insects)	TX	5
All Insects (Diptera, Coleoptera, Hemiptera, Colembolla)	**A:** 12.4 (of all macrofauna collected) **D:** 0-3,750 **B:** 0-0.3	TX	5

* See reference section for details.

The highly dynamic and variable environment of sand beaches displays an array of high temporal (e.g., seasonal changes in water, sand and air temperature) and spatial heterogeneity (e.g., changes in beach morphology, topography and water circulation) that have effects at different scales (hours to years; micrometers to meters), influencing biological, chemical and physical processes (Defeo and McLachlan, 2005; McLachlan and Hesp, 1984). This heterogeneity is responsible for the dynamic patterns in the spatial and temporal distribution of macrofauna, which are typically patchy in nature. This patchiness, coupled with relatively small sizes of most beach fauna, their movement with the tides, congregation around organic carbon sources, food availability, rapid burrowing behavior, and the occurrence of episodic events (dinoglagellate blooms, storms, large climatic events), adds to their non-random and irregular spatial and temporal distribution (McLachlan, 1983). Other factors contributing to these distribution patterns include transport and sorting of fauna by the swash, microhabitat selection, intraspecific and interspecific species interactions (e.g., competition, predation), and species-specific and age-class specific susceptibility to variations in the beach environment (see Defeo and McLachlan, 2005 and references herein).

The abundance, density, and biomass of the species of interest range widely between beaches, seasons, and years. There are some studies available on abundance and density for each species (Table 5-2); however, biomass data are scarce. The abundance of intertidal macrofauna in the northern GOM is the highest during summer (June-August) and lowest in winter (January-February). As a community, abundance can range from one individual per meter-wide transect to 1 million macrofaunal organisms, and spatial patchiness may also be high on a smaller scale, such as between closely spaced samples. McLachlan and Brown (2006) reported values between 100 and 10,000 as most typical. Defeo et al. (2009) reported that macrobenthic invertebrates in temperate zones can reach high abundance (100,000 individuals/m) and biomass (>1,000 g/m), particularly in dissipative to intermediate beach types. McLachlan (1983) reported abundance estimates from 105 beach surveys at 400 individuals/m^2 (high energy beach), 752 individuals/m^2 (medium energy beach), and 1,710 individuals/m^2 (low energy beach). Biomass values for these beaches were 2.26 g/m^2, 1.97 g/m^2, and 6.23 g/m^2 at the high, medium, and low energy beaches, respectively (McLachlan, 1983). McLachlan and Brown (2006) report that biomass values may range from less than 1 g dry mass per meter transect to 10 kg, with values between 10 and 1,000 g being typical. On two Texas sand beaches, Shelton and Roberston (1981) found mean macrofauna densities ranging from 1,398/m^2 (mainland beach- McFaddin) to 3,980/m^2 (barrier island- Malaquite), and mean biomass ranging from 5.23 g/m^2 (mainland beach- McFaddin) to 28.74 g/m^2 (barrier island- Malaquite). Some of the few studies in the GOM that have evaluated the spatial and seasonal variability in the composition, abundance and diversity of invertebrates of the swash zone (and subtidal beach areas) were conducted on 17 beaches of the Gulf Islands National Seashore (Figure 5-2) (Rakocinski et al., 1995, 1998a,b). These studies found that the swash zone of exposed beaches had a relatively smaller number of species (4-16), than the same zone within protected beaches (2-31), and that the number of species on exposed beaches was higher in the Mississippi district (west of Mobile Bay) than in the Florida district. While species richness was generally higher during summer and fall, density patters were less clear with regards to seasonality, and exhibited large spatial variability. Similar to species richness, density was also higher on protected beaches. Dominant species were also found, but their dominance patterns were clearer across seasons than across beaches within seasons. The same studies also indicated a much smaller number of species in the swash zone than in adjacent subtidal areas (5-15 m offshore), and a relatively fast recovery (within a year) following the impacts from two hurricanes (categories 1 and 5). Invertebrate geometric mean densities in the swash zone of exposed beaches prior (1993) and a year after the two hurricanes (1996) ranged from 98 to 1,374/m^2 and from 226 to 1,116/m^2, respectively, while on protected beaches densities ranged from 1,197 to 10,658/m^2 in 1993, and from 449 to 13,320/m^2 in 1996 (Rakocinski et al., 1998b). The GOM-studies mentioned above point at a very dynamic beach community assemblage that varies in composition, density and biomass at different spatial and temporal scales, making assessments of the impacts from the DWH spill and cleanup activities challenging.

The following sections provide more specific data on life history and community metrics for dominant species listed in Table 5-1. Although many species spend time on the entire beach face from the low tide line to the high tide line, there are distinct communities unique to each zone. Therefore, species are addressed according to the areas where they are most commonly found when surveyed.

5.2.2. Taxa, Densities, Distribution, and Life History of Sand-Associated Species

5.2.2.1. Upper Intertidal Zone

Talitrid amphipods are primarily found in the upper zones of sandy beaches in temperate latitudes (McLachlan and Brown, 2006). They are typically found among wrack and bury beneath these food sources while grazing on the plant material. They are also known to migrate from low to high tide in search of food (McLachlan and Brown, 2006). Talitrids move to the intertidal zone during the night to feed and burrow in the dunes and wrack during the day (de la Huz et al., 2005). Engelhard and Withers (1997) found that talitrid amphipods represented 1.7% of the major macrofaunal taxa collected from a Texas sand beach. Williams et al. (2008) observed the beach-endemic talitrid *Orchestia* spp. to be the most commonly found organism on Galveston Island, TX sand beaches.

Ocypode quadrata (ghost crab) is another upper intertidal zone invertebrate that burrows during the day and is surface-active mainly at night. This species is active from March through December and dormant during the winter months (Britton and Morton, 1989). Juveniles have shallow burrows (1 m) as they are typically found closer to the swash zone; adult ghost crabs are found from the swash zone landward toward the backshore with most burrows located above the drift line. The adult ghost crab burrows are typically deeper than juvenile burrows in order to have sufficient water supply. The burrows serve as protection from predators, harsh weather conditions, and provide a habitat for reproduction (Lucrezi and Schlacher, 2010). *O. quadrata* plays a key energetic role as the apex invertebrate predator and a major food source for higher trophic levels (e.g., birds). They are also prolific bioturbators (Schlacher et al., 2011) and one of the indicator species (i.e., species presence is indicative of the health of the ecosystem) listed for beach habitat in Florida's Comprehensive Wildlife Conservation Strategy (Irlandi and Arnold, 2008). Shelton and Robertson (1981) reported biomass values of 7 mg/m^2 and densities of 0.08 individuals/m^2 for *O. quadrata* on an exposed sand beach in Texas. Hobbs et al. (2008) recorded 0.02-0.13 individuals/m^2 on a North Carolina sand beach.

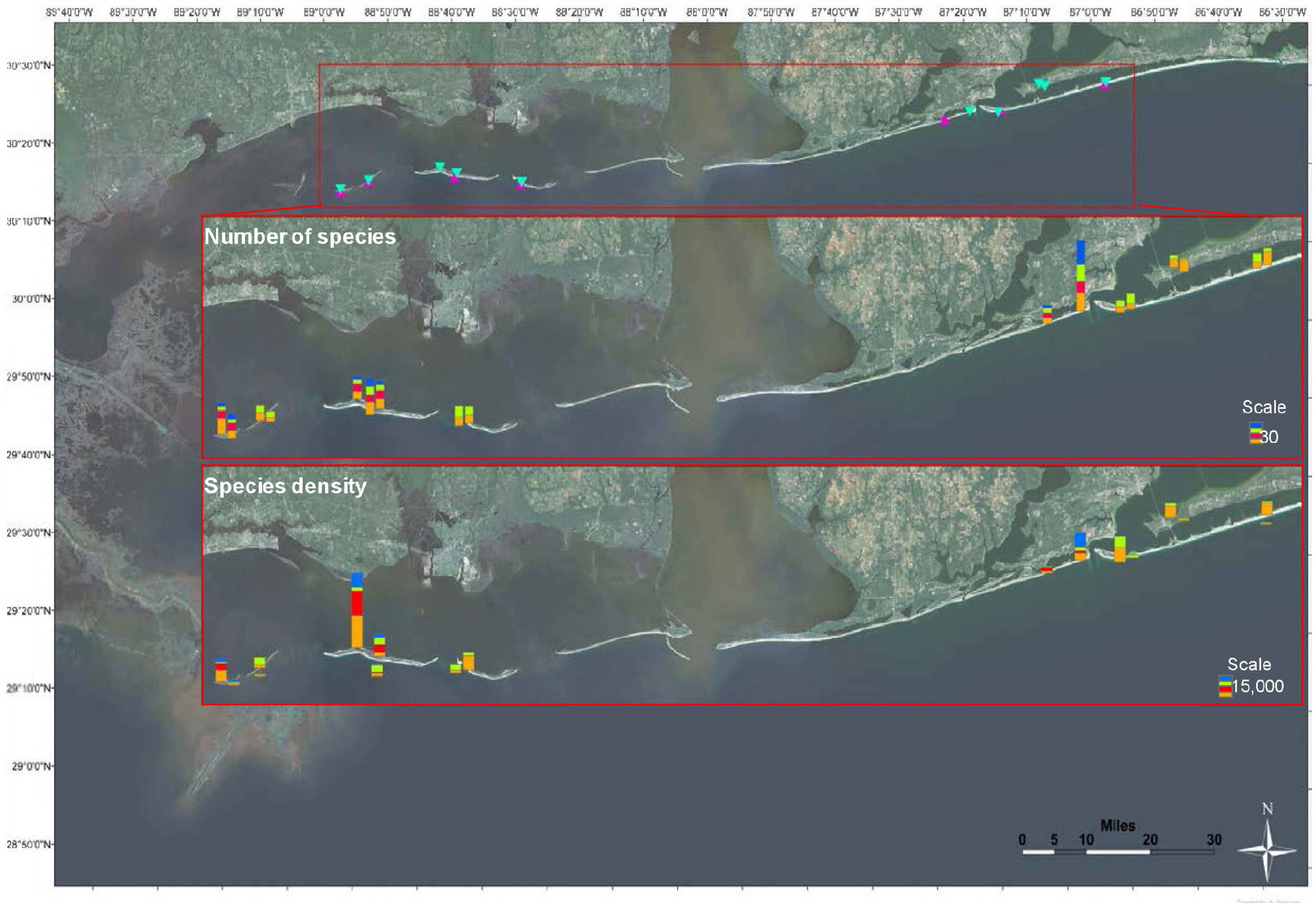

Figure 5-2. Spatial and temporal variability of invertebrates in the swash zone on beaches of the Gulf Islands National Seashore (# per 0.125 m^2). Note: not all sites were sampled quarterly. Symbols: beach types as exposed (▲), protected (▼); seasons: winter (■), spring (■), summer (■) fall (■). Reproduced from data in Rakocinski et al. (1995, 1998a).

Haustoriid amphipods (e.g., *Haustorius jayneae, Lepidactylus* spp.) are suspension feeders that can tolerate a wide range of environmental conditions and are capable of quick migration if disturbed. They can burrow beneath the sediments to depths of 12 cm, but are generally found within 5 cm of the surface (Engelhard and Withers, 1997). Keller and Pomory (2008) report that Haustoriid amphipods reach peak abundance in Florida during the late spring and summer months, with a minimum abundance from late fall through May. The highest numbers of Haustoriid amphipods are found in the middle to upper tidal zones, however, they can be found along the entire beach face. In fact mean densities of *H. jayneae* on the swash zone of selected beaches on the Gulf Islands National Seashore have been reported to range between 8-13,592/m^2 (Rakocinski et al., 1995). On some exposed beaches, this species tended to be one of the dominant species of the swash zone particularly during winter and spring (Rakocinski et al., 1998a). Shelton and Robertson (1981) found Haustoriid amphipods to be one of the numerically dominant species along two exposed Texas sand beaches, with a relative abundance of 66.1% and 30.3% at a barrier island beach and a mainland beach, respectively. Haustoriid biomass ranged from 0.37 g/m^2 (mainland beach- McFaddin) to 3.64 g/m^2 (barrier island-Malaquite), and densities from 423 individuals/m^2 (mainland beach) and 2,628 individuals/m^2 (barrier island) (Shelton and Robertson, 1981). Thebeau et al. (1981) recorded a wide range of densities (22-5,017 individuals/m^2) at thirteen transects surveyed along an exposed Texas beach impacted by the Ixtoc I oil spill.

Isopods are deposit-feeding crustaceans that can be found from the lower intertidal zone to the upper intertidal zone. Like amphipods, they reach peak abundance in the spring and summer with a decrease in abundance during the winter months (Keller and Pomory, 2008). Dexter (1972) recorded mean densities for *Ancinus* spp. of 103 individuals/m^2 and 80 individuals/m^2 on a sand beach on the Pacific and on the Atlantic coast of Panama, respectively. Biomass values recorded at these two sites were 0.204 g/m^2 and 0.194 g/m^2, respectively. At exposed sand beaches in Texas, Shelton and Robertson (1981) documented densities of *Ancinus depressus* of 5.86 individuals/m^2 (barrier island) and 16.6 individuals/m^2 (mainland beach), and biomass values of 3.44 mg/m^2 (barrier island) and 62 mg/m^2 (mainland beach). On swash zone-subtidal surveys of beaches at the Gulf Islands National Seashore, *A. depressus* were common on exposed beaches, but lacking particularly during fall from protected beaches (Rakocinski et al., 1998a).

5.2.2.2. Low to Middle Intertidal Zone

Donax is a dominant genus on sandy beaches worldwide. This invertebrate is a major food source for birds (e.g., plovers, sanderlings), fish (e.g., drum), and crabs (Rothschild, 2004). They inhabit beaches with medium to strong water currents. This bivalve is both subtidal and intertidal, moving up and down on the intertidal zone with the tides (McLachlan and Brown, 2006). Their movements across the beach face are cued by the vibrations of the waves on the shoreline (Rothschild, 2004). Keller and Pomory (2008) observed an increase in *Donax* on the Florida Panhandle in the summer months. Shelton and Robertson (1981) found *Donax* to be most abundant on Texas sand beaches in spring and summer in the low to middle intertidal zone with a subtidal movement during the winter. Recruitment of young occurred mainly in May and October (Rothschild, 2004). The density of this species is quite variable within and among studies, recording 10,000 and 22-6,542 individuals/m^2 in Texas (Getter et al., 1981; Thebeau et al., 1981, respectively), 264-334 individuals/m^2 in North Carolina (Peterson et al., 2000), and 72-13,114 individuals/m^2 in Florida (Mikkelson, 1981 cited in Irlandi and Arnold, 2008). Shelton and Robertson (1981) observed much higher values of *Donax* spp. on exposed sand beaches in Texas, recording 233 individuals/m^2 on a mainland beach and 871 individuals/m^2 on a barrier island beach. *D. variabilis* was one of the most common and dominant species in the swash zone of selected beaches on the Gulf Islands National Seashore, where their densities ranged from 8 to 1,272/m^2 (Rakocinski et al., 1995). On some exposed beaches, this species tended to be one of the dominant species of the swash zone particularly during summer and fall (Rakocinski et al., 1998a).

Emerita is also an extremely mobile and patchy animal typically found on moderately exposed surf-swept sand beaches (McLachlan and Brown, 2006). Like *Donax*, it also migrates up and down with the tides, and feeds via suspension feeding through the filtering of water with their antennae. *Emerita* found to be most abundant on exposed sand beaches between spring and fall in the Florida Panhandle and Mississippi/Alabama barrier islands (Rakocinski et al., 1998a). On selected beaches of the Gulf Islands National Seashore, the density of *E. talpoida* ranged from 8 to 6,608/m^2 (Rakocinski et al., 1995). In the GOM, eggs are produced in the spring and females carry these eggs during the summer months (Rothschild, 2004; Britton and Morton, 1989). A Florida study in the GOM found that *Emerita* larvae may be released in early summer and fall with recruitment of individuals also occurring at this time (Irlandi and Arnold, 2008). Peterson et al. (2000) found densities from 137-159 individuals/m^2 in North Carolina. *Donax* and *Emerita* are both considered indicator species for beach habitat in Florida's Comprehensive Wildlife Conservation Strategy (Irlandi and Arnold, 2008). Although their temporal variability has not been fully documented in beaches of the GOM, an earlier study on a beach in North Carolina found large changes in their abundance, spanning several orders of magnitude, over a 15-month period and particularly between April and November (Leber, 1982). *Emerita* and *Donax* appear to be important trophic links between planktonic and detrital energy sources and important beach predators such as portunid and ocypodid crabs, and shorebirds (Leber, 1982).

Another dominant species of sandy shoreline infaunal assemblages is the *Callichirus* genus (ghost shrimp). Endemic to the Gulf of Mexico, *Callichirus islagrande* lives in deep burrows (1-2 m) on the outer, more turbulent zones of exposed beaches (Bilodeau and Bourgeois, 2004). They can be found along the entire beach face from low to high intertidal habitats (Strasser and Felder, 2000). This animal plays an important role in oxygenating the sand through bioturbation of the sediments. A northern GOM study found that an increase in the flux of nutrients from the sediments and productivity of the benthic community was a result of the increased surface area from ghost crab burrows (Felder and Griffis, 1994). This study also observed an addition of organic matter, nutrients, and fine particles to the sediment surface from ghost crab fecal pellet ejection. The authors suggested that the loss of this species from the beach face may decrease the rate of sediment turnover and nutrient flux by prohibiting bioturbation. The breeding season of the *C. islagrande* is spring to fall (Strasser and Felder, 2000) and recruitment occurs biannually. Felder and Griffis (1994) documented a considerable seasonal and inter-annual variation with maximum densities observed in the fall, however numbers were drastically reduced with storm activity suggesting that wave energy may play a large role in abundance and distribution. Felder and Griffis (1994) found that densities ranged from 4-90 individuals/m^2 on a barrier island in Louisiana with a biomass of 70 g/m (dry weight) and 270 g/m (weight wet). Bilodeau and Bourgeois (2004) recorded similar densities on Louisiana barrier islands at 30-100 individuals/m^2. Shelton and Robertson (1981) recorded only a single individual from the two Texas sand beaches surveyed with a biomass of 21 mg/m^2. This species has also been documented on beaches of the Gulf Islands National Seashore (Rakocinski et al., 1995, 1998a), where they tend to be more common on exposed beaches particularly during the fall. Densities on these beaches ranged from 8 to 446/m^2 (Rakocinski et al., 1995).

Another group of common beach residents, polychaetes, are tube-dwelling or burrowing worms that suspension and deposit feed on detritus and organic material at the sediment surface (Engelhard and Withers, 1997). Polychaetes are not deep burrowers as they require aerobic conditions to support their feeding behavior; they are typically found in the upper layers of sediment. A common polychaete of the middle to lower tidal zone, *Scolelepis squamata*, is a fairly inactive species with low mobility. The absence of swimming activity makes this species particularly vulnerable to disturbance or contamination (Junoy et al., 2005). *S. squamata* has a peak in density in the summer (July) on Texas beaches (Engelhard and Withers, 1997) and in winter and spring on Mississippi beaches and the west coast beaches of Florida (Rakocinski et al., 1998a; Irlandi and Arnold, 2008, respectively). Thebeau et al. (1981) recorded densities of *S. squamata* between 22 and 1,658 individuals/m^2 along Texas beaches, and Rakocinski et al. (1995) reported densities from 8 to 3,536/m^2 on beaches of the Gulf Islands National Seashore. Shelton and Roberston (1981) saw much lower values during their study in Texas with densities ranging from 307 (barrier island) to 579 individuals/m^2 (mainland beach). This study also recorded biomass values of 0.33 (barrier island) and 0.45 g/m (mainland beach). Filho et al. (2009) recorded 350 individuals/m^2 of *S. squamata* on a Brazilian sand beach. *Dispio uncinata* is another beach polychaete most commonly found on protected beaches (Rakocinski et al., 1998a) at densities from 8 to 160/m^2 (Rakocinski et al., 1995).

Limulus polyphemus, the horseshoe crab, is present in the Gulf of Mexico but is not well studied in this region. Horseshoe crabs use the lower intertidal areas of exposed sandy beaches to spawn in an annual migration and then retreat back to shallow waters of the continental shelf (Walls et al., 2002). Adult females may spawn completely over several successive high tides (Botton and Ropes, 1987). The spawning season observed along Florida sand beaches is much longer than in areas along the Atlantic coast, sometimes occurring as early as February and continuing through the fall; high numbers of animals have been recorded in March and April with a single spawning event involving approximately 500-1000 individuals (T. Black, FWC, pers. comm.). Although animals have been observed in the winter months, their numbers are much reduced from December through early February. Horseshoe crabs are not a dominant species of the sandy beach in the northern GOM; however they do offer an important service in the lower intertidal zone by providing a food source (horseshoe crab eggs) to shorebirds. Adult females may produce as many as 88,000 eggs that are buried in the sand to a depth of between 5 and 30 cm in clumps of up to 3,650 eggs (Walls et al., 2002). Horseshoe crab larvae emerge between 2 and 4 weeks later through wave action and their own digging. They are released into the water where they remain to forage and grow (Walls et al., 2002).

5.3. Wrack and Wrack-Associated Species

Few studies are available on species associated with stranded wrack in the GOM. The literature that is available comes from studies conducted along the Texas coastline, specifically Padre Island National Seashore and Galveston Island. To broaden the knowledge of wrack and wrack-associated species, studies conducted in California were also included in this effort. Wrack has been studied in more detail on the sand beaches of California and even though the environment is quite different, some of those measurements are included here for comparison. Table 5-2 lists the life history data available for the dominant wrack-associated beach macrofauna of the northern GOM. Table 5-3 provides community metrics where available for these species.

Stranded wrack is generally deposited on Texas beaches between May and August (Engelhard and Withers, 1997; Williams et al., 2008). The most common species of wrack found along the Texas coast is the brown algae, *Sargassum natans*; however, *S. fruitans* and driftwood are also found in stranded wrack material (Engelhard and Withers, 1997). Masses of intertwined *Sargassum* mats may span over 100 m in length on the upper beach in Texas (Williams et al., 2008). A study conducted on Padre Island, Texas recorded that wrack biomass ranged from 0 to 650 g/m^2 (Engelhard and Withers, 1997). In this location, wrack was deposited in May and June and then decreased after the end of June. The Galveston Island study found biomass values ranging from 241 g to 1,387 g/0.5 m^2 (dry weight) (Williams et al., 2008).

California beach wrack is primarily giant kelp (*Macrocystis pyrifera*) and surfgrass (*Phyllospadix* spp.). The standing crop of wrack found on California beaches varies considerably and is likely related to the proximity of beaches to sources of wrack (e.g., rocky habitat and marine macrophyte beds) (Dugan et al., 2003). Dugan et al. (2000) estimated that the mean cover of wrack on ungroomed beaches of southern California ranged from 0.01-20.3 %. On groomed beaches, wrack volume ranged from 0.003 to 4.69 m^3 per running meter of beach. Dugan et al. (2003) estimated the input of wrack on sand beaches in southern California to be 473 kg wet weight/m/yr (Dugan et al., 2003) and 2.3 kg/m/day (Dugan et al., 2011). Dugan et al. (2011) recorded biomass values ranging from 0.41 to 46.4 kg/m.

Some of the ecological benefits of wrack include erosion control, beach stabilization, enhanced dune plant growth, and dune formation (Williams et al., 2008; Gheskiere et al., 2006). In addition, stranded wrack provides important habitat that supports a rich community of crustaceans and insects (Defeo et al., 2009). Stranded wrack is an important allochthonous source of carbon and organic material that affects all aspects of the trophic structure of the macrofaunal community on sand beaches (Dugan et al., 2003). The wrack itself is both a food source and a microhabitat refuge against desiccation for many sand beach invertebrates (e.g., ghost crabs, amphipods, isopods). The majority of wrack is biodegraded, passing though grazer and heterotrophic pathways. As stranded wrack decomposes and dries, the material is taken out to sea with the tides or blown off the beach (Engelhard and Withers, 1997). Species richness, biomass, and abundance of primary and secondary consumers, as well as the abundance of higher trophic level species (e.g., shorebirds) are all influenced by the input and fate of wrack (Dugan et al., 2003).

Wrack-associated organisms may comprise up to 40% of the intertidal species and represent an important prey source for higher trophic levels (Dugan et al., 2003). Dugan et al. (2000) found that species richness and abundance of selected taxa were positively correlated with macrophyte wrack cover. Dugan et al. (2003) recorded a mean abundance of 85 to 17,230 individuals/m for wrack-associated species in southern California. The density and species richness of Coleoptera (staphylinids, histeriids, and carabids) were greatest on beaches with high wrack input (5-11 species) and significantly reduced on beaches where wrack had been removed (0-2 species) (Dugan et al., 2003). This study also found that macrofauna associated with wrack only comprised <0.01-9% of the total macrofaunal biomass (ranging from 660 to >21,000 g/m) on sand beaches. The mean biomass of wrack-associated macrofauna was low, ranging from 1 to 390 g/m.

5.3.1. Taxa, Densities, Distribution, and Life History of Wrack and Wrack-Associated Species

Talitrid amphipods, ghost crabs, Haustoriid amphipods, and isopods (all discussed above as they are semi-aquatic organisms) are common organisms found in wrack (Nelson, 1993; Rothschild, 2004). Non-aquatic wrack species typically include wrack flies (Order Diptera), rove beetles (staphylinids; Order Coleoptera), and springtails (Order Collembola) (McLachlan and Brown, 2006). These species feed on decaying wrack as well as use the material for shelter.

Engelhard and Withers (1997) found that amphipods (Talitridae and Haustoriidae) comprised the majority of the wrack-associated macrofauna collected, representing 78.9% of the wrack community. The talitrid amphipod, *Orchestia grillus*, one of the most commonly found beach-endemics, is a detritivor that decomposes *Sargassum* and a primary contributor to biomass (Williams et al., 2008). This species peaks on Texas sand beaches from June through August and, along with insects, were the dominant grazers among the stranded wrack (Engelhard and Withers, 1997). Engelhard and Withers reported relative abundances of 1.7% and densities ranging from 0-600 individuals/m^2. The biomass values reported for *O. grillus* in this area ranged from 0-0.4 g/m^2. In southern California talitrid amphipods (*Megalorchestia* spp.) were the most abundant invertebrate in the wrack with a mean abundance ranging from 85 to 10,200 individuals/m and a biomass ranging from 1-378 g/m (Dugan et al., 2003).

Insects collected within the wrack were from the orders Coleoptera, Collembola, Hemiptera (nymphs) and Diptera (larvae), and represented 12.4% of the wrack macrofauna (Engelhard and Withers, 1997). The rove beetle (Order Coleoptera) was the most common insect collected representing 62.7% of the wrack insects. Diptera is typically the first to colonize stranded wrack, followed by beetles and other insects, and then amphipods. Engelhard and Withers (1997) reported peak densities for insects in mid-June and August along the Texas shoreline. The southern California wrack study reported density values for beetles (primarily Staphylind, *Bledius fenyesi*) from 51 to 5,160 individuals/m (Dugan et al., 2003). Junoy et al. (2005) documented Diptera densities of 4.9 individual/m^2 from sand beaches in Spain. Filho et al. (2009) recorded total insect densities of 50-100 individuals/m^2 during the dry and wet season, respectively, in Brazil.

6. Biological Effects from Oil and Oil Spills

In this section articles and reports on the effects of oil and oil constituents on intertidal invertebrates inhabiting sand beaches are reviewed. Efforts focused on studies within the region of concern, as well as on studies using relevant local invertebrate species. In the absence of Gulf specific studies, other relevant peer-review articles and reports were included in this synthesis. Additional sources of information were also requested from peers (J. Junoy, Universidad de Alcalá, Spain; J.W. Tunnell, Texas A&M; D. Homer, TetraTech; NOAA Damage Assessment Center and Office of Response and Restoration; National Park Service; U.S. Fish and Wildlife Service).

Search words and word combinations used in this section of the review included: sand beach, damage assessment, invertebrate toxicity testing, oil and weathered oil toxicity, oil spill effects, intertidal fauna, meiobenthos, macrobenthos, species sensitivity, species vulnerability, community structure, recovery rates, and acute and chronic effects.

6.1 Biological Effects from Historical Literature

Literature on the effects of oil spills on intertidal sand beach invertebrates is relatively limited. A handful of relevant documents have reported extremely variable impacts ranging from indiscernible effects (Gelin et al., 2003; Moore et al., 1997a) to evident impacts to the invertebrate communities (Blaylock and Houghton, 1989; Conan et al., 1982). These apparent discrepancies are likely the result of varying spill sizes, oiling extent, and re-oiling frequency, as well as the degree of oil weathering, site-specific sand beach geomorphology, initial composition of the invertebrate assemblage, and many other complex factors. Despite these large variations in documented effects, most studies have shown some level of impacts between oil and unoiled beaches that often have encompassed two phases: 1) an impact phase, where the associated invertebrate community experiences a dramatic reduction in species abundance and diversity caused mostly by mortality and oil fouling; and 2) a recovery phase, where the increased dominance of opportunistic, and changes in the structure of the characteristic species assemblage signal the start of the recovery.

Following the 1994 *MV Sea Transporter* oil spill off the Goa coast, Ansari and Ingole (2002) reported a short-term reduction in the density of dominant meiofauna taxa (including copepods and nematodes), followed by a relatively rapid recovery of nematodes. Given the observed patterns, the author did not anticipate long-term effects on the meiofauna community. Another study (Blaylock and Houghton, 1989) found that, at the most heavily oiled transects impacted by the 1985 *Arco Anchorage* oil spill off Port Angeles, Washington, heavy oiling combined with beach cleanup activities caused near complete mortality of the infaunal community. Several months later, the dominant invertebrate groups on heavily impacted transects were oligochaetes, nematodes, and polychaetes. Similarly, one week after the 2009 *Pacific Adventurer* spill, the lower beach of the oiled sites had significantly lower total abundance and species density compared to reference sites (Schlacher et al., 2010). These differences persisted three months after the spill, despite the lack of visual detection of oil. Following the 1978 *Amoco Cadiz* oil spill off the coast of Brittany, several authors (Boucher, 1980; Conan et al., 1982; Bodin, 1988) reported drastic quantitative and qualitative changes on the intertidal community. During the first week after the spill, extensive mortality was observed on intertidal communities of low-energy sand shorelines, including the collapse of the most resistant polychaete species (Conan et al., 1982). Seven months later, nematode abundance and diversity were generally depressed, even after a spring bloom (Boucher, 1980). The effects of the spill and the increased organic enrichment lasted much longer for copepods (3 years) than nematodes (2 years), and the original community was initially replaced by opportunistic fauna, likely less sensitive to the direct effects of hydrocarbon and dispersant toxicity, and more tolerant to oxygen depletion in sediments (Bodin, 1988). Three years after the spill, the community returned to its original structure.

A series of studies on the effects of oil on sand beach intertidal invertebrates were conducted following the *Prestige* oil spill off the coast of Galicia, Spain. This spill caused: 1) a notable decrease in total species richness (up to 67% of its species richness; De La Huz et al., 2005; Junoy et al., 2005), and depressed the abundance meiofauna (nematodes and copepods; Veiga et al., 2010) and macrofauna (dominant isopode and polychaete species; Junoy et al., 2005) several months post-spill; 2) complete elimination of rare species (including mollusks) within a year after the spill (De La Huz et al., 2005; Castellanos et al., 2007); and 3) disappearance of a commonly found nemertine species, *Psammamphiporus elongatus*, one to two years post-spill (Herrera-Bachiller et al., 2008). Macroinfauna abundance remained depressed even a couple of years after the spill (Castellanos et al., 2007). Changes on the intertidal community could not be explained by seasonal variations, and were attributed to the combined effects of oil and clean-up activities (Junoy et al., 2005; De La Huz et al., 2005). Interestingly, most of the changes in fauna abundance and composition occurred mostly on the middle and upper intertidal zone, where the oiling was highest (De La Huz et al., 2005; Junoy et al., 2005).

Perhaps some of the studies more relevant to the *Deepwater Horizon* oil spill were the assessments following the 1979 Ixtoc I blowout in Bay of Campeche, Gulf of Mexico (Hooper, 1981; Kindinger, 1981; Thebeau et al., 1981; Tunnell et al., 1981; Rabalais and Flint, 1983). Significant reductions of infaunal population densities were observed on the lower intertidal zone (Hooper, 1981). A month after the oil stranded, total faunal population densities were reduced by 64%, compared to pre-assessment levels (Kindinger, 1981; Tunnell et al., 1981). The intertidal community showed a decrease in total population densities between pre- and post-spill sampling periods, though these differences were not statistically significant (Thebeau et al., 1981). Although intertidal crustaceans, polychaetes and *Donax* spp. decreased by 89%, 51%, and 89%, respectively, relative to pre-impact levels, these changes may have been the result of multiple coexisting factors (including oil toxicity and smothering, storms, low water temperatures, beach erosion, and removal of food sources by clean up operations) (Thebeau et al., 1981; Tunnell et al., 1981). Several months after the spill, the intertidal community was largely dominated by the polychaete *Scolelepis squamata* (Rabalais and Flint, 1983), and major population declines were documented for mole crabs and amphipods (Hooper, 1981).

Studies from other catastrophic oil spills (i.e., Gulf War oil spills/releases) also provide information on the short- and long-term ecological effects of residual oil on sand habitats. Studies found that: 1) hardening of sediments and soil compaction by hydrocarbon residues represented a physical barrier for burrowing animals and limited crab resettlement (Barth, 2007); 2) oiled habitats with tar and buried oil had lower macrofauna diversity than reference sites because these residues prevented the return of the typical macrofauna community (Jones et al., 2008b); and 3) weathered oil and oil penetrated into sediments removed habitat from typical sand beach fauna (i.e., sandhoppers and crabs), and reduced the oxygen supply of the deeper sediment layer preventing recovery (Satoh et al., 1999).

Studies have also reported links between oil, oil residues and low hydrocarbon levels, and effects on sand beach communities. Following the *MV River Princess* oil spill, the site with the highest TPH value (89 μg/g) had a relatively low density of microbenthos (<10 individuals/ 3.3 cm^2), and TPH concentrations showed significant negative effects on macrofauna (i.e., invertebrate abundance-biomass comparison curves and polychaete/amphipod ratio) (Ingole et al., 2006). Junoy et al. (2005) reported a negative relation after the *Prestige* spill between degree of oiling and macrofauna species richness, which is consistent with Veiga et al. (2010), who concluded that six months after the spill, exposed sand beaches contained PAHs at concentrations high enough to cause negative impacts on the benthic fauna. By contrast, Strand et al. (1990) found that relatively low concentrations of hydrocarbons in mollusk tissues collected from oiled beaches two years after the *Nestucca* oil spill reflected a continuous exposure to residual oil buried within oiled beach sediments, but that the low oil residues in sediment likely would not cause severe long-term impacts on the intertidal community.

6.2. Oil Toxicity

A relatively large body of literature exists from laboratory bioassays data on a variety of marine invertebrates exposed to water accommodated fractions (see Table 6-1). Lethal effects occur in the 1-1000 μg/L range or at lower concentrations (0.1-10 μg/L) in smaller, more sensitive life stages, while sub-lethal effects typically occur in the range of 1-10 ng/L (see Suchanek 1993 and references therein). However, comparisons among studies are often difficult because of inherent differences in test exposures and conditions (duration, preparation of water-soluble fractions, endpoints), as well on reporting metric (total petroleum hydrocarbons vs. total aromatic hydrocarbons vs. chrysene equivalents) and analytical techniques (UV spectrofluorometry vs. Gas Chromatography-Mass Spectrometry (CG-MS) vs. GC-FID). Toxicity data from tests using water accommodated fractions, however, must be interpreted with caution as laboratory conditions rarely reflect the conditions in the field. Under controlled laboratory conditions, it is difficult to simulate the processes that influence oil behavior and toxicity, including dissolution, evaporation and photo-oxidation, and burial. Despite these challenges, various laboratory toxicity testing studies using field samples from sand beaches impacted by oil spills have been valuable in characterizing risks to indigenous invertebrate species. Toxicity testing with intertidal sediments collected from sand beaches a few days after the *Prestige* oil spill was inconclusive with regards to toxicological effects on bivalve or sea urchin larvae species (Beiras and Saco-Alvarez, 2006). A similar study related to the same incident found moderate toxicity of sand elutriates to sea urchin larvae (15% reduction in larval length), though other factors may have contributed to these effects (Fernández Méijome et al., 2006). A 11-month monitoring study using the mussel *Mytilus galloprovincialis* found significantly higher DNA damage in mussel gills (evaluated by the comet assay) from specimens collected at two beaches impacted by the *Prestige* oil spill compared to reference mussels (Laffon et al., 2006). These DNA damages were positively correlated with total PAH concentration in seawater from the same areas. Although the authors found indications DNA repair during a recovery stage in clean seawater, mussels from the oil-exposed beaches still had higher DNA damage than reference specimens (Laffon et al., 2006). By contrast sediment testing with field sediments from the *Sea Empress* spill showed reduced copepod hatching success 2 months after the spill, and improved hatching 4 months after the spill, but not to the level seen in control substrate (Moore et al., 1997b).

Laboratory testing has also shown differences in sensitivity to oil and oil residues within life stages of the same species. Earlier work involving exposures to water accommodated fractions of South Louisiana crude of the polychaete *Neanthes arenaceodentata* (Rossi and Anderson, 1976) found a much lower sensitivity of juveniles compared to adults possibly due to a greater concentration of yolk matter, which may have sequestered the more toxic hydrocarbon fractions. Another study documented differences between reproductively active and non-reproductively active ghost crabs (*Ocypode quadrata*) to oil exposures (Jackson et al., 1981). Reproductively active crabs showed greater sensitivity to oil possibly due to the reduced ability of reproductive individuals to cope with the stress as their energy demands and metabolic requirements increase during gametogenesis. Aside from the direct toxicity caused by oil, oil stranded on beaches can also change the physical characteristics of the substrate (obstruction of interstitial sand pores, alteration of water flow and depletion of oxygen).

Although there are relatively a few studies on the effects of oil spills on sand beach intertidal bivalves and mussels (see above), literature exists on the effects of PAH contaminated media on these sentinel organisms. Despite obvious differences across studies in chemical analysis (GC/MS vs. HPLC) and reporting (number of PAHs analyzed, tissue concentrations in dry or wet weight) most of such research on bivalves reported cellular stress linked to PAH exposure (Krishnakumar et al., 1997; Fernley et al., 2000; Toro et al., 2003; Francioni et al., 2007). These studies attribute increase in cellular stress to a series of cellular alterations including the activation of catalyzing multifunctional enzymes (i.e., gluthatione-S-transferase) involved in the metabolism of xenobiotics, and increased oxidative stress (i.e., formation of DNA adducts and production of lipid peroxidation). Increased lysosomal destabilization has also shown a strong correlation with decreased total antioxidant capacity in cells (Regoli, 2000), indicative of compromised efficiency in neutralizing strong oxidizing chemical species, and increased micronuclei frequency, indicative of severe chromosomal damage (Kalpaxis et al., 2004). Other studies have also shown that bivalves exposed to PAH contaminated sediments reduces the number of haemocytes, may interfere with the maturation/differentiation of haemocytes, and inhibits phagocytic activity (Sami et al., 1992; Grundy et al., 1996a, 1996b; Pichaud et al., 2008), which are key processes in immune response. Although severe immunosuppression in mussels *Mytilus edulis* was documented during the first two months following the *Sea Empress* spill, recovery occurred a few months later indicating that the initial effects were not permanent (Dyrynda et al., 2000). By contrast, several immune-related parameters in *Crassostrea gigas* (granulocytes, phagocytosis, and oxidative activities) 13 months after the *Hebei Spirit* oil spill were depressed compared to oysters from a control site (Donaghy et al., 2010). High lysosomal activity in *M. edulis* has been documented during periods of stressful conditions (e.g., spawning, high temperatures, reduced food quality), which have resulted in mass mortalities associated with tissue autophagy (Tremblay et al., 1998). Similarly, induction of heat-shock proteins in *C. gigas* have been documented in post-spawning oysters indicating that post-spawning oysters have compromised thermo-tolerance and immune response, increasing their vulnerability to post-spawning stressors (Li et al., 2007). Consequently, bivalves undergoing stress associated with physiological processes may also be more susceptible to the effects from exposure to other stressors, including oil residues and PAHs. Although studies with bivalves are important to characterize effects to these species, these organisms are relatively tolerant to contaminants, thus lack of effects in bivalves do not indicate lack of potential toxicity to other invertebrates.

Table 6-1. Summary of toxicity testing of intertidal invertebrates or close relatives. Not all of the references described in this document have an associated summary within this section. TAH: total aromatic hydrocarbons; THC: total hydrocarbons compounds; TPH: total petroleum hydrocarbons; WSF: water-soluble fractions; WAF: water accommodated fraction

Test Organism	Crude Oil Source (media)	Test Type (toxicity endpoint[1])	Toxicity Endpoint	Comments	Reference
Sand crab *Emerita analoga*	Weathered South Louisiana crude (WAF)	6 day static renewal (LC50; EC50)	7.1 and 1.2 mg/L TPH	This exposure media was lethally toxic to the sand crab and inhibited growth. Emergence and molting were not affected.	Barron et al. (1999)
Ghost crab *Ocypode quadrata*	Kuwait crude oil	96 hour flow through (LC50 on crabs on reproductive and non reproductive crabs)	0.19 mg/L and 1.35 mg/L TPH	Reproductively active individuals were more susceptible to oil than non reproductively active crabs	Jackson et al. (1981)
Shore crab *Hemigrapsus nudus* File periwinkle *Nucella lima* Blue mussel *Mytilus trossulus*	Cook Inlet crude (WAF)	4 day flow through (LC50)	>3 mg/L TAH	These species were less sensitive to oil than fish or subtidal species	Moles (1998)
Bivalve *Mercenaria* spp.- embryo	South Louisiana crude (WAF)	48 hour static (LC50)	5.7 mg/L WSF	Over a 48 hr exposure period, embryos were more sensitive than larvae	Byrne and Calder (1977)
Bivalve *Mercenaria* spp.- larvae		2, 6, and 10 day static (LC50)	6, 5.3 and 2.1 mg/L WSF		
Polychaete *Capitella capitata* - adult	South Louisiana crude (WAF)	96 hour static (LC50)	9.8 mg/L TPH	-	Rossi et al. (1976)
Nereid polychaete *Neanthes arenaceodentata* - juvenile Nereid polychaete *Neanthes arenaceodentata* - adult	South Louisiana crude (WAF)	96 hour static (LC50)	15.2->19.8 mg/L THC 12.5-18.1 mg/L THC	Toxicity increased with age and size	Rossi and Anderson (1976)
Polychaete *Cirriformia spirabrancha*- juvenile Polychaete *Ctenodrilus serratus*- juvenile Polychaete *Ophryotrocha puerilis*- juvenile Polychaete *Ophryotrocha* spp. - juvenile	South Louisiana crude (WAF)	28 day static test (LC50)	19.8 mg/L TPH >19.8 mg/L TPH 17.2 mg/L TPH 12.9 mg/L TPH	Different polychaete species exhibited different sensitivities to oil. *C serratus* was the least sensitive, suggesting its use as indicator species	Carr and Reish (1977)

[1]EC_{50}: effective concentration that affects 50% of the exposed organisms; LC_{50}: lethal concentration that affects 50% of the exposed organisms

6.4. Biological Recovery

Data from previous spills have usually shown a greater than one year recovery time of the invertebrate community on sand beaches, though recoveries have been documented to range between 0.5 to 5 years (Table 6-2; Wormald 1976; Giere, 1979; Boucher, 1980; Raffin et al., 1981; Bodin, 1988; Ansari and Ingole, 2002; Barth 2002; and others). Six months after the 1975 Florida Keys oil spill, Chan (1976) did not observe oily debris, and the macrofauna abundance was similar to that of an unoiled beach. Moore et al. (1997a) also found no evidences of major impacts on the meiofauna community nine months after the *Sea Empress* oil spill, and only in the most severely impacted areas recovery of burrowing invertebrate populations required at least two full years (Moore, 2006). Amphipod densities and population levels of two long-lived species (spiny cockle and heart urchin) were still low two and ten years, respectively after the spill (Moore, 2006). In contrast, a longer recovery was documented by Blaylock and Houghton (1989), who noted that three years after the *Arco Anchorage* spill the infaunal assemblage and residual oil concentrations on sand beaches were similar to pre-spill conditions. Perhaps one of the longest sand beach recoveries was required following the Gulf War oil spills. Barth (2002) found that high-energy sand beaches completely recovered after five years, while low energy beaches (20% of the total impacted sand beaches) were almost completely recovered ten years after the spill. Data from experimental studies also provide valuable information on the response and recovery of invertebrates to oil exposures. The benthic fauna in sediments oiled with Forties oil (Schratzberger et al., 2003) showed shifts in dominance patterns, reduced nematode species, and absence of rare species eleven weeks post treatment; however, the structure of the nematode assemblage resembled that of unoiled sediments 45 weeks post treatment. In a similar study (Vanderhorst et al., 1980) 15 months after sands were oiled with Prudhoe Bay crude, the fauna abundance was 48-75% of the non-treated sands, and the invertebrate community was largely dominated, in number of species and abundance, by polychaetes. Full community recovery in oil-treated sands was estimated at 31 months post treatment.

Based on the body of literature available, it is clear that the recovery of the intertidal community after an oil spill is not only dependent on the persistence of the oil and on beach dynamics and characteristics (shoreline type, degree of exposure, beach geomorphology), but also reliant on the invertebrate community assemblage and species-specific characteristics (their sensitivity to residual toxic compounds in the sediment, recruitment pattern of the affected species, and their life history traits). Buried oil on sand beaches and the intertidal zone can persist from years to decades (Long et al., 1987; Barth, 2002; Jones et al., 2008b; Short et al., 2007), particularly in the absence of cleanup activities, or in the absence of strong physical forces of natural attenuation (e.g., tidal flushing, wave action, erosion/deposition cycles). Not surprisingly, exposed high-energy sand beaches recover faster from an oil spill than low-energy sand beaches (Bodin, 1988; Barth, 2002; Michel et al., 2008). The recovery times reported here are generally in agreement with those from an earlier report (AURIS, 1995). For tropical beaches, that report documented recovery times between five months and two years for treated beaches, and from four months to five years for untreated beaches. For boreal and temperate beaches, the same report documented biological effects between one and six years, with no biological recoveries for seven years.

Table 6-2. Studies or reports with documented or estimated recovery of sand beaches relative to baseline, pre-spill, or compared to controls.

Oil Spill Name	Oiling Condition	Metric	Indicator species	Effect/Impacts	Estimated Recovery (years)	Reference
1978 Peck Slip, Pasaje de San Juan, PR	Light to Moderate	Macrofauna associated with wrack	Amphipods	Visible effects on supratidal beach grasses, intertidal wrack (mortality of amphipods), and subtidal grass beds	0.3	Gundlach et al. (1979)
1975 Florida Keys Oil Spill	Heavy	Macrofauna abundance	Amphipods, crabs	Macrofauna were not found in the oiled grass or in the oil-soaked sand	0.5	Chan (1976)
1973 diesel spill in Picnic Bay, Hong Kong	Heavy	Meiofauna community	Harpacticoid copepods, nematodes	Drastic quantitative changes of the meiofauna community within the first eight months after the spill	1.25	Wormald (1976)
1985 *Arco Anchorage*, Ediz Hook, WA	Heavy	Infaunal biomass, abundance, diversity	Bivalves, crustaceans, polychaetes	Oiling and beach cleanup caused near-complete mortality of the infaunal community	2	Blaylock and Houghton (1989)
2007 *Cosco Busan*, San Francisco Bay, CA[1]	Very light to heavy	Impacts on the intertidal community	Invertebrates	Invertebrates may have been fouled and killed by oil, and removal of wrack during cleanup may have removed associated fauna	3	USFW Service (pers. comm.)
2003 *T/B Bouchard*, Buzzards Bay, MA[1]	Very light to heavy	Impacts on the meio- and macrofauna community	Meio- and macrobenthos	Invertebrates may have been stranded, smothered and killed by oil, and removal of wrack during cleanup may have removed associated fauna	3.5	Michel et al. (2008)
1978 *Amoco Cadiz*, Brittany, France	Not reported	Copepod and nematode abundance; copepod species richness and community structure	Harpacticoid copepods, nematodes	Drastic quantitative and qualitative changes of the meiofauna community from hydrocarbon and dispersant toxicity, and oxygen depletion	3-5	Bodin (1988)
1991 Gulf War Oil Spills	Heavy	Species diversity and abundance	Invertebrates	The oil decimated beach invertebrates, with species diversity returning to normal levels 2-3 years after the spills. Complete recovery of high-energy beaches took 5 years, whereas some low energy beaches recovered 10 years after the spills.	5	Barth (2002)

[1]Information generated based on published literature and best professional judgment.

The recovery of the intertidal community is also a function of the sensitivity of the species within the community to oil and oil residue exposures (see for example Conan et al., 1982). Studies (Moles, 1998 and references therein) have noted that intertidal invertebrates appear to be less sensitive to oil (at least in acute exposures to water soluble fractions) than fish and subtidal invertebrates, partially because they have adapted to withstand the stresses of their habitat. Moles (1998) also recognized that sand beach intertidal species are vulnerable to chronic oil pollution, particularly those inhabiting areas where the oil is likely to persist for long periods of time (sheltered, low oxygen content, etc.). Crustaceans are among the most commonly affected benthic invertebrate taxa by hydrocarbon contamination. Amphipods can experience temporary local extinctions (Gesteira and Dauvin, 2000; Gesteira and Dauvin, 2005), and their slow recovery (≥5 years) to pre-spill abundances and body length, particularly of ampeliscid amphipods, further suggests high sensitivity to chronic exposures of residual oil (see Suchanek 1993 and references therein). Interestingly, Junoy et al., (2005) reported that amphipods were the least impacted invertebrate after the *Prestige* oil spill. Copepods and nematodes also appear to be relatively sensitive to hydrocarbon exposure, and in several instances, nematodes appear to recover quicker from exposure than copepods within the same impacted beach (for example 1 vs. 8 months, respectively, in Wormald, 1976; Giere, 1979; Ansari and Ingole, 2002; Veiga et al., 2010). By contrast, the density of nematodes and copepods at the most heavily oiled waver exposed sand beaches impacted by the *Sea Empress* spill did not show marked reductions relative to clean sites (Moore et al., 1997a), whereas amphipods and mud snails found on sheltered muddy sand shores were severely reduced 3 months after the spill (Moore et al., 1997b). Members of the meiofauna community, such as oligochaetes, polychaetes, halacarians and turbellarians, have often been regarded as rather insensitive to oil pollution (Giere, 1979). While polychaetes generally decrease in abundance following spills, their response has also been more variable than that of other invertebrates (De La Huz et al., 2005; Gesteira and Dauvin, 2005; Junoy et al., 2005). Barth (2002) also noted that some oiled areas 10 years after the Gulf War spills were void of invertebrates, while others were characterized by the presence of polychaetes only.

Life history traits particularly fecundity, dispersal and recruitment characteristics, growth rates and life span, also play an important role in the recovery of intertidal sand beach communities (Conan et al., 1982; Schlacher et al., 2010 and references therein). Isopods, amphipods, and some species of polychaetes that exhibit direct embryonic development may recover less quickly from extensive acute impact, as recolonization requires recruits from neighboring unimpacted populations (Schlacher et al., 2010 and references therein). The timing of a spill can also greatly influence the recovery of species. Scarlett et al. (2007), for instance, indicated that given the reproductive cycle of amphipods, a spill occurring in early summer would have more severe impacts on amphipod growth rates than a spill later in the year.

Habitat recovery may be better evaluated based on ecosystem functions (e.g., re-establishment of a functional biological community, trophic interactions and biodiversity levels; biomass and productivity) rather than on species abundance and population structures. Ecosystem functions are typically grouped into: 1) large scale regulation of services and processes including biogeochemical cycles (e.g., nutrients, water, organic carbon), buffering capacity (e.g., shoreline stabilization and erosion); 2) habitat for several species occupying diverse trophic levels and life stages (e.g., invertebrate and fish nursery, bird and turtle nesting), which ensures the maintenance of genetic and biological flow and biodiversity; 3) supporting natural processes that maintain direct and indirect goods and services derived from habitats (i.e., primary productivity, food sources for higher trophic levels); and 4) human-related provisioning values including recreation (United Nations Millennium Assessment, 2005; Schlacher et al., 2008a). Intertidal invertebrates are key components of the beach ecosystem, and as such they contribute to ecosystem functions. Studies in riparian ecosystems (see Cummins et al., 2001) have grouped invertebrates into three functional relationships groups based on their ecological roles with the ecosystem they inhabit. These groups are based on feeding strategies (functional-feeding groups), interaction with the habitat including locomotion and substrate interactions (functional-habit groups), and life history (voltinism). The abundance/biomass/dominance of these functional groups can be used as a measure of ecosystem health (i.e., gross production, substrate stability, food availability for fish and birds, community succession), thus these can be used as indicators of restored ecosystem functions.

Although it is intuitively logical to think that dramatic changes on the invertebrate assemblages from the decline in abundance or extirpation of species that contribute significantly to the structure and maintenance of community interactions can result in larger ecological processes within the habitat, these links are extremely difficult to demonstrate. Several studies (see Kennedy and Jacoby, 1999 and Defeo et al., 2009 and references therein) argue that changes in the attributes of the invertebrate community can translate effects at lower and higher trophic levels, as well as into a reduced ecological value of the entire ecosystem. Felder and Griffis (1994) also indicated that the loss of burrowing populations from nearshore habitats caused by physical or biological disturbances would decrease the rate of sediment turnover and nutrient flux. However, the potential large-scale ecological consequences of reduced abundance and biomass of the invertebrate community following oil spills are difficult to quantify. One study (Chapman 1984) following the Ixtoc I spill looked at data from avian abundance and distribution, and pre- and post-impact beach infauna densities, and suggested that the spill lowered the carrying capacity of the foreshore, though bird populations recovered without exhibiting permanent effects. Similar studies have documented impacts at higher levels of biological organization from cleanup activities and beach grooming, but these will be discussed in a later section in the report.

Finally, field information on the baseline condition of the invertebrate community is commonly unknown, and its spatial (i.e., patchy distribution) and temporal (i.e., fluctuating seasonally and annually) dynamics make quantitative assessments challenging. These issues can hinder the ability to numerically quantify impacts on these communities, mask species-specific responses to oil and oil related stress, and can lead to conflicting or inconclusive results on their response to disturbances. These challenges should be taken into consideration when measuring the recovery of the sand beach invertebrate community form the impacts of the DWH.

7. Biological Effects from Response-Disturbances and Related Activities

In this section, articles and reports on the effects of human activities, including compaction, desiccation, crushing and trampling on intertidal invertebrates inhabiting sand beaches are reviewed. This section includes articles and reports from previous oil spill responses, as well as other activities (beach grooming, wrack removal, restoration) that may have comparable effects to those resulting from response activities. Efforts focused on studies within the region of concern, as well as on studies using relevant local invertebrate species. In the absence of Gulf specific studies, other relevant peer-review articles and reports were included in this synthesis. Additional sources of information were also requested from peers (LM

Weslawski, Institute of Oceanology PAS, Poland; NOAA Damage Assessment Center and Office of Response and Restoration; U.S. Fish and Wildlife Service).

Search words and word combinations used in this section of the review included: sand beach, oil spill, cleanup activities, beach restoration, wrack removal, beach cleaning, beach grooming, mechanical cleaning.

7.1 Response Activity Impacts from Historical Literature

Micro-, meio- and macrofauna interactions in sand beaches are regulated by the presence of organic carbon sources at the beach surface. Beach wrack, for example, is considered of high ecological importance (Dugan et al., 2000; Dugan et al., 2003) as it plays both physical and ecological roles. Wrack enhances the organic and moisture content of the beach substrate, helps stabilize the foreshore, protects the beachfront from wind erosion, and promotes the proliferation of dune plants. Wrack is also the link between invertebrate communities that use this material as a food source, shelter and microhabitat for invertebrates (i.e., amphipods, isopods, juvenile crabs, insects), and higher trophic levels (crabs and shorebirds) preying on these invertebrate communities. Studies have shown that species richness and abundance, and biomass of wrack-associated invertebrate fauna, such as talitrid amphipods, are significantly correlated with the standing crop of macrophyte wrack (Dugan et al., 2000; Dugan et al., 2003). Therefore, maintaining the surface and subsurface habitat structure and quality is essential in sustaining invertebrate communities and species interactions within the beach habitat. Cleanup activities that remove oiled wrack, or that remove oiled sand and its associated carbon source, can eliminate the resources that support invertebrate communities, and can also reduce the abundance and biomass or even eliminate keystone beach species. Thus, these activities have the potential to disrupt the energy budget and balance of the beach ecosystem.

Intertidal communities on sand beaches are frequently thought as rather tolerant to disturbances because they are well adapted to the unstable and dynamic nature of the beach environment. However, this fauna can be impacted through cleanup operations by crushing, changing habitat suitability (substrate compaction or softening), disrupting reproduction and recruitment patterns, altering or removing food supplies, or remobilizing oil residues (Chan, 1976; Blaylock and Houghton, 1989; De La Huz et al., 2005; Michel et al., 2008; Borzone and Rosa, 2009). The combined effects of oiling and cleanup activities have shown to alter the composition of talitrid amphipods (Borzone and Rosa, 2009), reduce species richness and eliminate entire species (De La Huz et al., 2005), and cause near complete mortality of the infaunal community (Blaylock and Houghton, 1989).

7.2. Physical Disturbance

7.2.1. Sediment Removal and Placement

Cleanup operations can also be equated with beach nourishment projects, as in the latter sand is mechanically moved and redistributed on the beach surface, resulting in sizable changes in the sand beach ecosystem (beach profile, morphology, substrate compaction), as well as in temporary changes to the beach inhabitants (flora and fauna). Studies have documented changes to the intertidal community resulting from beach nourishment projects and related activities. Some of these studies found that: 1) slow recovery of an intertidal clam (*Donax*) population was noted after a nourishment project that replaced the original substrate with sediment containing high levels of shell fragments (Peterson et al., 2000); 2) macrobenthos exhibited slow recoveries after a nourishment project that increased concentration of fine sediments (Rakocinski et al., 1996); 3) changes in grain size and slope from disposal of mine tailing were correlated with decreased species richness and macrobenthic abundance, and this activity was attributed to the disappearance of the local *Donax* species (McLachlan, 1996); 4) nourishment projects that coincide with the recruitment period of indicator species can have large impacts on invertebrate populations (Cobb and Arnold, 2008), and 5) beach nourishment can lead to low species diversity, richness and equitability compared to pre-nourishment levels (Reilly and Bellis, 1983). Major disruptions of the sand beach surface can have significant impacts at the population (demography and dynamics), community (species richness), and ecosystem (functional processes, nutrient flux, trophic dynamics) levels (Defeo et al., 2009). Furthermore, the reduction in the abundance and biomass of dominant species has been linked to disturbances in the foraging behavior of shorebirds and to reduced habitat productivity (see Defeo et al., 2009 and references therein; Peterson et al., 2006). However, others (Nelson and Collins, 1987) have also reported no measurable effects of nourishment projects on indicator species.

Beach nourishment can cause immediate ecological damage to the resident sand beach invertebrate community including complete mortality of resident intertidal biota. Bilodeau and Bourgeois (2004) evaluated the impacts of beach nourishment projects on the conspicuous ghost shrimp, *Callichirus islagrande,* at two barrier islands of the Isles Dernieres chain of Louisiana (East and Trinity Islands). Two and a half years post-restoration, these restored beaches did not have the large densities of ghost shrimp seen at reference sites within the chain of islands, which had generally well-established populations. Only a few juveniles and one ovigerous female were found, indicating that the population did not show any signs of recolonization or recruitment. The lack of recolonization was attributed to changes in the sediment composition. Sand beach restoration projects on the eastern Atlantic have also shown impacts on dominant members of the intertidal community (Peterson et al., 2000; Lindquist and Manning, 2001; Peterson et al., 2006). Lindquist and Manning (2001) evaluated the impacts of beach nourishment and mechanical redistribution of beach sand (bulldozing) on dominant intertidal macroinvertebrates, and found significant declines in the abundance of ghost crabs (*Ocypode quadrata*) 6 to 8 months post-bulldozing. Possible explanations for this decline included the substantial changes in the sand composition, which likely impeded the formation of stable burrow structures; and/or the timing of the bulldozing (mid-November to March), which may have caused direct mortality through burying as these activities coincided with the season when crabs are permanently below ground. Bulldozing also reduced the abundance of mole crabs (*Emerita talpoida*), though these changes were not statistically significant from controls. Other species (i.e., coquina clams *Donax variabilis*, spionid polychaete *Scolelepis squamata*, and amphipod *Amphiporeia virginiana*) appeared to have escaped the impacts of bulldozing as their abundances resembled those of control beaches. In contrast, Peterson et al. (2000) found that both beach nourishment and bulldozing had quantifiable effects on intertidal species 5 to 10 weeks post treatment compared to control beaches. Nourishment reduced the density of two dominant species, mole crab and bivalve mollusks (*Donax* spp.) by 99% and 86%, respectively, possibly by altering the composition of the substrate; whereas bulldozing reduced the abundance of mole crabs and ghost crabs active burrows by 37% and 65%, respectively, probably by changing the beach morphology enough to reduce the habitat suitability for intertidal macroinvertebrates. Peterson et al. (2006) also attributed large mass mortality of benthic macroinfauna to beach filling (nourishment). Over several months post-treatment, *Donax* spp. and amphipods had much higher abundances (85% and 89%, respectively), and ghost crab burrow density across the flat beach were up to twice as high on undisturbed control beaches; in contrast, ghost crab summertime recruitment appeared to have been inhibited on filled beaches. Evidence of the effect of sand disturbance on invertebrates has also been documented in other parts of the world. In Australia, a beach nourishment caused the elimination of the amphipod, *Exoediceros fossor*, with some signs of recovery seen 9 weeks later (Jones et al., 2008a); and in South Africa, a single excavation event removed sand to a depth of 0.3 m (Schoeman et al., 2000) causing temporary changes in the abundance of macrofauna. This community required 7-16 days to recover following a single disturbance event.

Beach nourishment projects or major sand beach cleanup operations that cause compaction of the substrate can be particularly problematic to the invertebrate community. Compaction increases the bulk density of the substrate, and reduces the interstitial space thereby reducing the capillarity, water retention, permeability and the exchange of gases and nutrients within the substrate matrix (USACE, 1989; Defeo et al., 2009). Compaction also increases the penetration resistance obstructing the construction of burrows, which can impact burrowing behavior and reduce the abundance of burrowing fauna (Lindquist and Manning, 2001). The overall impacts of compaction can be translated into reduced substrate productivity and microhabitat suitability (Lindquist and Manning, 2001).

7.2.2. Beach Grooming and Wrack Removal

The large majority of documented effects on invertebrates come from periodical grooming of wrack from amenity beaches (Dugan et al., 2000; Gheskiere et al., 2005; Weslawski et al., 2000a; Weslawski et al., 2000b), while only a few are from activities associated with oil cleanup (Chan 1976; Blaylock and Houghton, 1989; De La Huz et al., 2005; Michel et al., 2008; Borzone and Rosa, 2009). Defeo et al. (2009) indicated that, in general, macrobenthic populations and communities respond negatively to increased human activity levels. Beach grooming activities that remove wrack have significant effects on the community structure (depressed species richness, abundance, and biomass) of wrack-associated fauna, causing significant ecological consequences, including the substantial reduction of prey for higher trophic levels (Dugan et al., 2000; Dugan et al., 2003; Defeo et al., 2009) and, depending on the spatial scale of grooming (<1 to 100 km), the effects could be noticeable at scales ranging from weeks to years (Defeo et al., 2009). For example, temporal mechanical raking (0-3 cm penetration) for wrack removal on the upper intertidal zone at Padre Island National Seashore lowered the mean density and biomass of all macrofauna within three days post-raking, and the density and biomass of the amphipod *Orchestia grillus* and polychaetes up to 10 days post-raking, compared to unraked areas (Engelhard and Withers, 1997). Studies in Europe (Weslawski et al., 2000a; Weslawski et al., 2000b; Malm et al., 2004; Gheskiere et al., 2005; Gheskiere et al., 2006) have also reported the biological and ecological impacts of beach cleaning. At two tourist beaches, removal of wrack with mechanical beach cleaners reduced the percent total organic matter in the upper beach zone and caused high community stress (i.e., lowered invertebrate diversities, the number of distinctive taxa and genetic diversity, caused replacement of species with higher number of opportunist species), compared to non-tourist beaches (Gheskiere et al., 2005). In a related study, the top 5 cm of sand surface was removed with mechanical beach cleaners (Gheskiere et al., 2006). This short-lived disturbance caused significant changes in the total abundance and community structure immediately after cleaning by reducing the abundance of dominant nematode species (*Theristus otoplanobius*, *Trissonchulus benepapilosus*, *Chromadorina germanica*) and harpacticoid copepods, which recovered completely following two tide cycles. In Sweden, beach cleaning caused significant changes in the organic content of sediments (Malm et al., 2004). Cleaned beaches had a much lower level of organic carbon than un-cleaned beaches, and the most intensively cleaned beaches had lower total benthic biomass. However, biodiversity and community structure were not significantly different between cleaned and un-cleaned beaches. Weslawski (Weslawski et al., 2000a; Weslawski et al., 2000b) has extensively documented the effects of beach cleaning in Poland. He suggested that trampling and mechanical cleaning may have contributed to the disappearance of air-breathing amphipods or sandhoppers from the most frequently visited beaches (Weslawski et al., 2000a; Weslawski et al., 2000b and citations therein). Furthermore, wrack removal from the upper layer of sand and sand sifting through a 5 mm sieve effectively removes important food sources for key species, which are linked to disappearance of macrofauna and the decline of their predators (Weslawski et al., 2000b and citations therein). This author also indicated foot traffic (3,000 steps/m^2 day) caused sufficient beach fragmentation, and mixed debris with sediment down to 10-30 cm.

7.2.3. Off-Road Vehicle Traffic

Off road traffic on sand beaches (i.e., four-wheelers and small vehicles) is an activity that has been studied relatively extensively and that is somewhat comparable to cleanup activities. Recent studies (Schlacher et al., 2008b; Schlacher and Thompson, 2008) indicated that the effects of anthropogenic disturbance on local invertebrate assemblages vary greatly depending on their spatial and seasonal occurrence and abundance, and on their specific life histories. Schlacher et al. (2007) found that ghost crabs are frequently crushed by off road traffic if their burrows are relatively shallow (5 cm), and that this species is particularly vulnerable because of its soft exoskeleton. Not surprisingly, ghost crab mortality declined exponentially with burrow depth. Schlacher et al. (2007) also found that ghost crab densities were higher in areas subjected to low to moderate traffic, while individuals were smaller in heavily impacted areas, suggesting alterations of the population structure. Beaches with heavy off road traffic also had lower abundance, species richness, and diversity of intertidal macrobenthos, and strong changes in the community structure were driven by the low abundances of the cirolanid isopod *Pseudolana concinna* (Schlacher et al., 2008b). Direct crushing appeared to be the main cause of community changes. Lucrezi and Schlacher (2010) also reported that sand beaches impacted by traffic were slightly hotter and had lower moisture content than beaches closed to traffic, and that on vehicle-impacted beaches not only were ghost crabs smaller, but also constructed much deeper and longer burrows possibly to avoid desiccation. Another study (Kluft and Ginsberg, 2009) demonstrated that vehicle traffic can degrade the quality of beach wrack by crushing, scattering or burying, impacting the survival of invertebrates that depend on this habitat for food and shelter. For example, open-beach species (i.e., the beach hopper *Talorchestia longicornis* and the wolf spider *Arctosa littoralis*) were more susceptible to disturbance than wrack inhabitants (enchytraeid oligochaetes and tethinid flies *Tethina parvula*). The former were likely crushed in their shallow burrows during daylight traffic, while the latter (interstitial detritivores) may have benefited from the increased moisture and mechanical breakdown of the wrack by vehicle traffic. Gastropod species, on the other hand, appeared to be most resistant than soft-bodied invertebrates (mysid and isopod) to vehicle traffic (Van Der Merwe, 1991). Aside from direct crushing, heavy traffic decreases invertebrate abundance by reducing food availability (including wrack), increasing species displacement, disrupting the intertidal habitat and the physical properties of the sand substrate, and increasing invertebrate exposure to predators from the continuous maintenance of burrows (Schlacher et al., 2007; Kluft and Ginsberg, 2009). Many of these factors in turn can influence recruitment.

From the studies mentioned thus far, it is clear that species susceptibility to off road traffic, as well as beach cleaning and grooming, is largely dependent on body size, species fragility (soft vs. hard bodies), turnover rates, and burrowing behavior (deep vs. shallow). Generally, large-scale operations would be more detrimental to species that: 1) brood their young; 2) have a soft exoskeleton; 3) have larger sizes and lower turnover rates; 4) build shallow burrows; 5) have seasonal reproductive cycles that coincide with cleaning activities; 6) occur at high densities in soft, non-compacted sand; and 6) are more closely associated with the substrate, and therefore are more strongly impacted by changes in the structure of the sand matrix (compaction) (Van Der Merwe, 1991; Schlacher et al., 2007; Jones et al., 2008a; Schlacher et al., 2008b).

7.3. Recovery from Physical Disturbance

Recovery of the indigenous communities will, on the other hand, depend on the intensity/frequency of impacts (see Table 7-1) and their co-occurrence with important biological processes (e.g., recruitment), and will largely be controlled by the survival of the resident fauna and on their life history traits. Habitat recolonization occurs through reproduction of the surviving individuals, dispersal of planktonic larvae, alongshore sediment drift that facilitates movement of adults or juveniles from adjacent populations, or immigration from deeper sands (Peterson et al., 2006; Jones et al., 2008a; Borzone and Rosa, 2009). Although invertebrates may recover quickly from a pulse disturbance (Engelhard and Withers, 1997; Schoeman et al., 2000; Gheskiere et al., 2006), studies have cautioned against deep, intense, and repeated sand cleaning because these activities can greatly impact the invertebrate sand communities and can compromise recolonization (Engelhard and Withers, 1997; Weslawski et al., 2000b; Gheskiere et al., 2006; Borzone and Rosa, 2009).

The short-term impacts of cleanup and related activities are rather obvious as these will likely cause large mortalities of benthic species. Although the larger ecological implications of these activities are more ambiguous, large-scale disturbances can translate into impacts at higher trophic levels (Lindquist and Manning, 2001; Peterson et al., 2006).

Table 7-1. Studies documenting the effects of grooming and oil cleanup activities on intertidal invertebrates in sand habitats.

Purpose (duration)	Operation Type or Cleanup Method	Metric	Indicator Species	Effect/ Impacts	Estimated Recovery	Reference
Grooming of beach wrack (regular event)	Heavy equipment	Wrack-associated macrofauna	Talitrid amphipods, isopods, coleopteran, beetles	Significant effects on community structure, including reduced species richness, abundance, and biomass	N/A	Dugan et al. (2003)
Beach nourishment project (single event)	Heavy equipment; Large scale bulldozing and beach nourishment	Density of dominant species, and burrow density	Mole crab *Emerita talpoida*, bivalve mollusks *Donax* spp. and ghost crabs *Ocypode quadrata*	Reduced density of mole crabs and bivalves on nourishment beaches, and reduced ghost crab burrows and mole crab abundance on bulldozed beaches	NA	Peterson et al. (2000)
Grooming of beach algae and wrack from an amenity beach (single event)	Scraping of the upper sand layer (5 cm) with a fast-turning wheel equipped with shovels (540 rotations/ min) and a 30 mm mesh sieve	Meiofauna species abundance and community structure	Nematodes and harpacticoid copepods	Differences in meiofaunal community and community structure within the first hours post cleanup	Within the second high water (<24 h)	Gheskiere et al. (2006)
Disturbance experimental (single event)	Excavation of 60 m^3 of sand to a depth of 0.3 m (total area of 200 m^2)	Species richness, macrofaunal abundance, and abundance and biomass of the dominant infauna	Macrobenthic community, beach clam *Donax serra*	Reduced mean macrofauna abundance, and reduced abundance and biomass of the beach clam	7-10 days	Schoeman et al. (2000)

Table 7-1. Continued.

Purpose (duration)	Operation Type or Cleanup Method	Metric	Indicator Species	Effect/ Impacts	Estimated Recovery	Reference
Raking of beach wrack (regular event)	Mechanical raking to a depth of 3 cm	Macrofauna abundance and biomass	Amphipods, insects and polychaetes	Density and biomass reduction of all, and in particular of wrack associated fauna (*O. grillus* and polychaetes)	>10 days	Engelhard and Withers (1997)
Beach nourishment project (single event)	Heavy equipment; Large scale sand extraction and beach nourishment	Amphipod abundance	Amphipods	Complete elimination of amphipods	Initial recovery: 9-13 weeks; complete recovery <1 year	Jones et al. (2008a)
Beach filling (single event)	Heavy equipment; Large scale beach filling	Density of dominant species, and burrow density	Bivalve *Donax* spp., mole crab *Emerita talpoida*, haustoriid amphipods, and polychaetes and ghost crabs *Ocypode quadrata*	Reduced abundance of bivalves and amphipods, and reduced density of ghost crab burrows	At least one warm season	Peterson et al. (2006)
Beach nourishment project (single event)	Large scale beach nourishment	Density of dominant species and indices of community structure	Mole crab *Emerita talpoida*, bivalve mollusks *Donax* spp., ghost crabs *Ocypode quadrata* and burrowing amphipod *Haustorius canadensis*	Significant effects on community structure, and complete elimination of important beach species, and inhibition of recruitment	One to two seasons post-nourishment	Reilly and Bellis (1983)

8. RESPONSE ACTIVITIES EFFECTS ON BEACH MORPHOLOGY

Beach morphology may be affected by the following types of response activities:

- Sediment removal could lead to increased erosion rates of the shoreline
- Excavation and temporary side casting of clean sediment to access buried oil could lead to changes in the beach profile and localized shoreline erosion
- Mechanical tilling/sifting of the backbeach areas could lead to increased erosion via aeolian transport of the disturbed surface and/or decreased compaction
- Vehicle traffic could lead to damage to vegetation and sediment compaction
- Response operations could result in the prevention of new beach/dune plant establishment due to continuous disturbance by vehicles, equipment, and personnel. As a result, the beaches and edges of dunes remain absent of vegetation, which contributes to erosion after the next storm. Without such disturbance, the dunes would naturally migrate seaward.
- Sand washing (conducted only on Grand Isle) of sand mechanically removed from beaches was stockpiled on the backbeach, then spread at the high-tide line at locations different from where the sand was removed, could lead to localized changes in shoreline erosion and deposition

The volume of sediment removed from sand beaches will be part of the total weight or volume of oiled materials that have been removed from the beaches. There are multiple efforts to compile these numbers by shoreline segment, or other spatial groupings, which will be needed to determine the potential for increased beach erosion. Longshore sediment transport rates in the north-central Gulf of Mexico range from on the order of tens of thousands of cubic meters per year to over 200,000 m^3/yr with values commonly 50,000-100,000 m^3/yr (Rosati and Stone, 2009; Ellis and Stone, 2006; Stone and Staphor, 1996). The volumes of sand likely removed from the beaches will have to be compared against these rates to determine if sand removal will be a significant factor on shoreline erosion.

The treatment methods on sand beaches were designed to minimize the volume of sediment removal through the use of sand sifters to separate SRBs and SRPs from clean sand using both manual and mechanical sifters. Manual sifting included the use of screened rakes where workers sift piles of sand by shaking in air or washing in water at the water's edge. They also used screened sift boxes, shaking the boxes to separate the oil from the sand. Mechanical sifting was conducted using a range of equipment types: 1) small, walk-behind "Sandman" units that were similar to lawnmowers in size; 2) mobile sand cleaning equipment such as the self-propelled Cherringtons and towed Sand Shark; and 3) a fixed sifting machine where the sand was brought to the unit and sifted into large piles for later redistribution. Each type of equipment would have a different degree of potential impacts to beach morphology, with the greatest impacts likely related to methods where the sand was removed and transported to a fixed location for treatment (e.g., the fixed sifting machines).

Mechanical tilling (use of harrows to break up buried oil and bring it to the surface for removal by sand sifters) has been allowed on several beaches, and has been extensively used on the backbeach areas on Grand Isle, LA. Tilling will initially increase the drag coefficient, which is one of the key factors in calculating the shear velocity, which affects the rate of aeolian sand transport (Dingler et al., 1992). However, the tilled area was subsequently passed over by sand sifters/cleaners, which tended to smooth the surface. Owens (1998) summarized the case studies where tilling was used; the objective is to accelerate natural removal by exposing the oil and oiled sediments to a higher degree of physical abrasion and other physical and biochemical degradation and weathering processes.

Two other papers were found on the use of tilling as an in-situ treatment method for intertidal sediments. Baca et al. (2005) conducted a six-month test to treat oil residues on a sand beach in Kuwait, thirteen years after the 1991 Gulf War oil spill using powdered bacteria products with nutrients, tilling, raking, and screening. The site that was tilled, raked weekly for 2 months, then screened showed significant reductions. According to Baca et al. (2005):

> "The failure of bioremediation chemicals to degrade the 13-year old oil at the site is probably a function of the age of the oil and the field conditions rather than the abilities of these chemicals which have a proven track record. Those who have worked on the Gulf war spill stress aeration and increasing surface area (Michel, pers. comm.) as best means of enhancing degradation of this oil. The use of raking to break up larger asphalts, followed by screening to remove smaller, denser particles, can greatly enhance this process."

Smith (1996) conducted a test one year after the Gulf War oil spill on a sandy mud tidal flat in Saudi Arabia using: 1) dry tilling in strips 100 m long and 10 m wide, perpendicular to the shoreline; 2) High-pressure sea water jet flushing to a depth of 30 cm, towed behind a tractor in water depths of 7 cm, with released oil floating to the surface for recovery by skimmers. The tilled site showed about 50% reduction in total oil and the aliphatics in the top 5 cm and 32 and 46% reduction in the 5-15 cm depth at the spring tide site, but no detectable change at the neap tide site. When comparing the chromatograms, the oil from the upper tilled site was more degraded than from the adjacent non-tilled site. The higher degradation of the spring tide tilled site is also indicated by the reduction in the two indices comparing nC_{17}/pristine and nC_{18} to phytane. Visually, the tilled site looked much less oiled and more oxygenated. The author recommended tilling as an important treatment to break up thick oil layers and speed the natural rates of biodegradation.

There have been concerns that tilling would affect beach compaction, and thus erosion potential. A study of different tilling techniques (rotary cultivator, beach sand cleaner, disk harrow and excavator) during an 8-month experiment on inland drift-sand areas in Holland (Riksen and Goossens, 2005) found no change in the bulk density after tilling with any of these techniques. Tilling has been used extensively as a method to loosen the sand placed on nourished beaches in Florida because of concerns that the compacted sand would be harder for sea turtles to excavate during nesting (Nelson, 1987). Nelson and Dickerson (1988) showed that a tilled nourished beach will remain uncompacted for up to one year. Davis et al. (1999) conducted a study to determine the effect on compaction of tilling to 92 cm on a beach in Pinellas County, FL as measured with a cone penetrometer. They reported large spatial and temporal variability in compaction measurements, an initial decrease in compaction at the tilled site (though similar decrease at an untilled site), and an increase in compaction after two months at the tilled site.

Sediment relocation, also known as surf washing, (where sand is mechanically or manually moved from the supratidal or intertidal zone to the water to accelerate natural reworking by wave action) has been allowed on Grand Isle, LA, mainly by using small bobcat equipment to dump small loads of "stained" sand (sand that had been treated by other methods to remove the SRBs and SRPs) into the surf zone. There are no estimates of the volume of sand "surf washed" in this manner. Owens et al. (1995) and Owens (1998) argue that sediment relocation is an effective method for polishing of stained sand. The objective is to accelerate the two natural cleaning processes of physical abrasion and oil-fines interaction.

Aeolian sand transport on beaches can be significant. Dingler et al. (1992) measured 1.26 m^3/m of sand transport on Trinity Island, LA during four days of strong northerly winds during the passage of a cold front, causing erosion of the backbeach and accretion at the beachface. However, they were able to account for all the sand within the area between the dunes and the waterline, so there was no net loss of sand for this one storm.

9. IDENTIFIED DATA GAPS AND RESEARCH NEEDS

9.1 Geomorphology and Beach Profile Changes

The following topics related to geomorphology and beach profile changes have been identified as data gaps during this literature review:

- The volumes of sand removed from specific sand beaches are being compiled by the Response Injury Working Group. As soon as these data are available, they should be compared with data on sediment transport rates and net changes in sand volume on representative beaches to determine the significance of sand removal. At a minimum, the amount of sand removed can be used to determine the additional amount of sand to be added to a beach during the next planned nourishment project.
- The beach profile data being collected by the SCAT Program should be requested as soon as it is available (raw and processed). These data will provide the best information on changes in beach morphology for the sand beaches affected by the spill. However, because most of the sand beaches most heavily oiled and treated are also highly erosional and erosion is mostly related to the passage of storm events, it will be difficult to quantitatively determine how the treatment has affected both short- and long-term erosion rates and beach profile changes.
- There is no strong evidence that tilling causes changes to beach stability. Because tilling is a common requirement on nourished beaches that are important for sea turtle nesting, it may be possible to seek out personal experience of land managers where this has occurred.

In addition, the Trustees may want to request time-series beach profile data (raw and processed) from the SCAT program.

9.2 Existing Biological Resources

The following topics on existing biological resources have been identified as data gaps during this literature review:

- A list of the common or dominant benthic invertebrates of sand beaches of the Chandeleur Islands and Louisiana barrier islands. Life history and community metrics for these species are also needed.
- A list of the common or dominant wrack-associated species for all four regions
- Data on the cover, biomass, or volume of wrack found on beaches in the Gulf of Mexico
- Data on life history and community metrics (mainly density and biomass) for wrack-associated species
- Abundance and biomass data for sand-associated species
- Information on spatial and temporal variability of macro benthic communities at different scales

With an input of freshwater from the rivers along the Louisiana coastline and other environmental parameters (e.g., sediment grain size), species present on sand beaches from the barrier island chain of Isle Dernieres to the Chandeleurs are likely to be somewhat varied from the barrier islands of Mississippi, Alabama, and Florida. However, we have located few sources on the sand beach invertebrates that are typically found in this region. There are numerous restoration studies on the Louisiana barrier islands. Unfortunately, none of the data collected included information on the flora or fauna of the intertidal sandy substrates.

There are also no studies on beach wrack or species found within wrack from Louisiana to the Florida Panhandle. We included data from the study on Padre Island National Seashore, Texas (Engelhard and Withers, 1997) and on Southern California beaches (Dugan et al., 2000; 2003) to provide some information on wrack and wrack-associated macrofauna. Studies of the amount of wrack that is typically found along the sand beach shorelines in each of the locations of interest, as well as the time it takes for invertebrates and natural processes to cause the breakdown and disappearance of wrack are needed. Studies on the duration of replenishing lost wrack would also be important to the Sand Beach TWG since oiled wrack was removed from the shoreline during the response.

As a result of the lack of community metrics available for dominant sand beach invertebrates of the Gulf of Mexico, studies from other regions (e.g., Atlantic and Pacific Coasts, South America) were used where the source provided life history data for organisms of at least the same genus. If a different region was used to supplement the data, the region was listed in Tables 5-2 and 5-3.

9.3 Biological Effects from Oil and Oil Spills

The following topics related to the biological effects from oil and oil spills have been identified as data gaps during this literature review:

- Literature on the effects of oil spills on intertidal sand beach invertebrates is relatively limited, and are currently restricted to a handful of spills including the *Amoco Cadiz*, *Arco Anchorage*, *MV Sea Transporter*, *Pacific Adventurer*, *Prestige*, and Ixtoc I.
- Not all studies have reported the links between oil, oil residues, and low hydrocarbon levels, and effects on sand beach communities

- Many of the factors that influenced the effects and recovery (e.g., climate, beach type, and wave energy) have varied from one oil spill to another, and therefore direct comparisons to effect of the DWH spill on sand beach communities is difficult.
- Although several studies have evaluated the effects of the water-accommodated fractions of oil on marine invertebrates, these may not be necessarily comparable to the exposure conditions following the *Deepwater Horizon*. Additional oil toxicity testing, particularly under realistic environmental exposure concentrations are needed to elucidate the link between exposure and effects for this spill where physical and secondary effects (e.g., smothering, fouling, avoidance, oxygen depletion, etc.) may be as important and chemical toxicity. These tests should also consider toxicity and exposure within the context of periodic emersion and desiccation, when applicable.
- Additional information is needed regarding species-specific and life stage-specific sensitivity to residual toxic compounds in sediments and in pore water. Additionally, efforts are needed to characterize acute and chronic toxicity to weathered Macondo crude oil in these habitats, with emphasis on realistic environmental exposures. Special focus should be given to assessing the effects of chronic exposures on reproductive success and recruitment
- Toxicity testing should consider the use of common or dominant benthic invertebrates of sand beaches in the Gulf of Mexico, or alternatively explore the use of suitable surrogates.
- The recovery of these communities is also poorly understood, and therefore site- and region-specific metrics need to be evaluated to adequately quantify injuries to these habitats (see Table 9-1)
- There is paucity of studies linking the large-scale ecological implications of reduced abundance and biomass of the invertebrate community following oil spills. Mesocosm studies and trophic transfer analysis may be helpful in identifying the links among trophic levels in the beach environment
- There are data gaps on the basic understanding of the ecosystem functions of the communities inhabiting beach habitats, such as understanding baseline conditions of functional biological communities, trophic interactions and energy budgets, temporal and spatial biodiversity, biomass, and productivity
- Literature on the effects of and recovery rates from physical disturbances from response activities on intertidal sand beach invertebrates is scarce and pertinent literature is available primarily from related beach activities (e.g., beach nourishment projects, beach grooming and wrack removal, and off-road vehicle traffic). Considering the extent and duration of such physical disturbances, it will be difficult to assess the ecological consequences
- To adequately quantify the degree of ecological services lost and the rates of recovery for the different sand beach injury categories, future research should focus on compiling, synthesizing and estimating important metrics including: biomass and productivity, invertebrate assemblages (community structure, diversity and composition), life history and spatial and temporal distribution of representative and key-stone species, measures of response of key species to disturbances and chronic residual oil exposures, and similar measures of recovery.

In order to assess the recovery process following an oil spill it is important to understand the baseline pre-spill condition. These initial conditions represent the natural spatial and temporal patterns of single species or assemblages, which could be used measure speed of recovery as well as the time to a complete recovery. Ecological recovery from an oils spill can be viewed in two general (not strict) phases. The first phase occurs following an oil spill and the start of cleanup activities (see next section). During this phase, receptor or indicator species may suffer temporal declines beyond those expected from natural events. This does not imply that in all cases the indicator species or communities are complete eradicated by these actions, or that their natural variability is in all cases much lower than pre-spill conditions. The recovery process (second phase) encompasses an initial colonization of fast-growing and sometimes opportunistic species, followed by a recovery period, where the community gradually reaches its natural structure. A complete recovery can also occur upon the return of the community assemblage, trophic interactions and ecological functions within the ranges of natural variability (see Figure 9-1). However, the recovery process, which may take from days to years, is highly dynamic, and it depends not only on the degree of oiling and the cleanup intensity, but also on site-specific physical and biological factors (Table 9-1). Biological factors that may play a role in recovery include species-specific life history traits such as life span, fecundity rates, seasonality of reproductive processes, reproductive strategies, and degree of dependency on the substrate, among others. Therefore, assessing the recovery would benefit from a general understanding of the baseline conditions of species and communities (as well as their life histories, and natural patterns of spatial and temporal variability) inhabiting sand beaches of the Gulf of Mexico (Figure 9-1). Field information on the baseline condition of the invertebrate community is commonly unknown, and its spatial (i.e., patchy distribution) and temporal (i.e., fluctuating seasonally and annually) dynamics make quantitative assessments challenging. These issues can hinder the ability to numerically quantify impacts on these communities, mask species-specific responses to oil and cleanup activities, and can lead to conflicting or inconclusive results on their response to disturbances. These challenges should be taken into consideration when measuring the recovery of the sand beach invertebrate community form the impacts of the DWH.

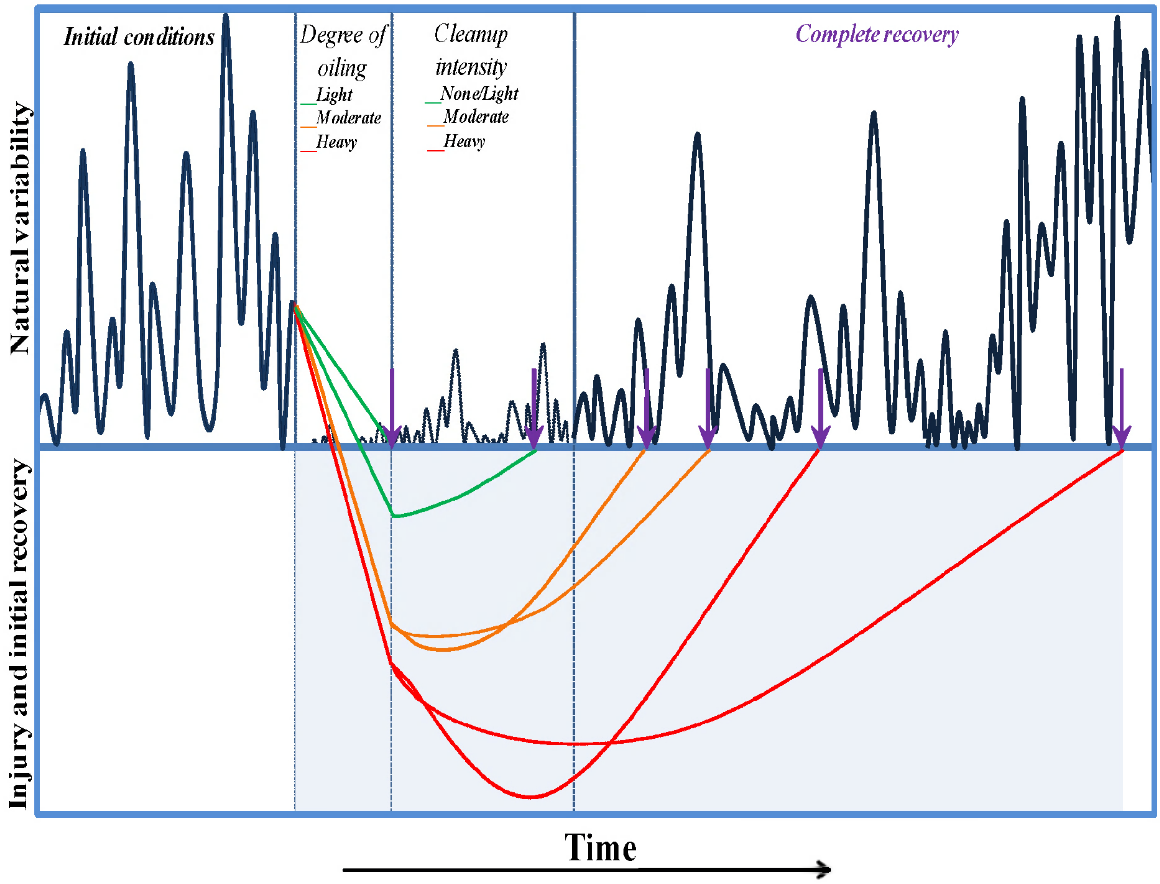

Figure 9-1. General stages of the ecological recovery following oil spills. Initial condition: natural spatial/temporal variability of an indicator species/community prior to the spill; Oil spill and cleanup phases: effects on the initial conditions are likely a function of the extent, duration and magnitude of the oiling, and cleanup intensity. This does not imply that in all cases the indicator species or communities are complete eradicated by these actions, or that their natural variability is in all cases much lower than pre-spill conditions; and recovery process: the time to recovery depends on a variety of abiotic/biotic factors, with complete recovery reached with the return to initial conditions.

Table 9-1. Examples of factors that may contribute to recovery rates of invertebrate communities on intertidal sand beaches. The anticipated recovery times are a continuum, based on site-specific physical and biological factors and their continuum. *Note:* to be used only as a guide; not all possible contributing factors are included.

Attributes	Recovery time		
	Weeks →	Months →	Years
Oiling Degree	• Very Light/Light	• Light/Moderate	• Moderate/Heavy
Extent of Oiling	• Oil deposited on the surface oiling in the upper intertidal zone • Oil rapidly removed as a result of cleanup	• Oil buried in intertidal and supratidal zone • Oil rapidly removed as a result of cleanup	• Oil buried in intertidal and supratidal zone • Chronic re-oiling occurs
Biota	• High fecundity • Early maturity • Short life cycle (<0.5 year) • High offspring dispersal ability • High recruitment/exchange from nearby areas • Planktonic larvae • High mobility • Rafting (associated with mobile substrates) life stages • High exchange with nearby beaches • Simple biological interactions (e.g., food webs)	• Short life-cycle (<1 year) • Soft bodies • Recruitment coinciding with oiling/cleanup • All life stages associated with substrate • Low to high recruitment/exchange from nearby areas • Between low mobility and sessile • Rafting (associated with mobile substrates) life stages	• Long life cycles (>1 year) • Semi-terrestrial • Lack of pelagic larvae • Lack of offspring phase dispersal • Slow development • Limited to no recruitment/exchange from nearby areas • Isolated populations • Mostly sessile • Non rafting (associated with mobile substrates) life stages • Complex biological interactions (e.g., food webs) • Important biological processes occur concurrent with spill/cleanup activities
Environment	• High-energy environment (waves and/or currents) • Beach is dynamic, with frequent erosion/deposition events • Beach sediments are well flushed and aerobic	• Moderate-energy environment • Beach is stable • Beach sediments are moderately flushed and there are some anaerobic layers	• Low-energy environment • Beach is very stable • Beach sediments are poorly flushed and anaerobic
Cleanup activities	• Limited in space and short duration • Removal of surface sediments only • Minimal sediment removal • Minimal removal of wrack • No mechanical removal methods	• Moderate in space and multiple treatments • Removal of surface and shallow subsurface sediments • Moderate removal of wrack • Shallow mechanical removal	• Intensive, deep, frequent treatment • Widespread cleanup of deeply buried oil • Frequent removal of wrack • High traffic of heavy equipment

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APPENDIX – BIBLIOGRAPHIC SUMMARIES

A. GEOLOGY/GEOMORPHOLOGY

Author: Baca, B., M. Al-Sarawi, and T.W. Kana (2005)
Title: Recent bioremediation results on oil spilled during the 1991 Gulf War
Source: Proc. 2005 International Oil Spill Conference
Methods: Powdered bacteria products with nutrients, tilling, raking, and screening were used as in-situ methods to treat oil residues on a sand beach in Kuwait 13 years after the Gulf War oil spill.
Findings/Summary: None of the bioremediation chemical treatments showed any decrease in oil content. Site that was tilled, raked weekly for 2 months, then screened showed significant reductions. According to the authors:

> "The failure of bioremediation chemicals to degrade the 13-year old oil at the site is probably a function of the age of the oil and the field conditions rather than the abilities of these chemicals which have a proven track record. Those who have worked on the Gulf war spill stress aeration and increasing surface area (Michel, pers. comm.) as best means of enhancing degradation of this oil. The use of raking to break up larger asphalts, followed by screening to remove smaller, denser particles, can greatly enhance this process."

Author: Cipriani, L. E. and G. W. Stone (2001)
Title: Net longshore sediment transport and textural changes in beach sediments along the southwest Alabama and Mississippi barrier islands, U.S.A.
Source: *Journal of Coastal Research* **17**: 443-458
Findings/Summary: This study used computer simulations of net longshore sediment transport between Dauphin Island, Alabama, and West Ship Island, Mississippi to predict six distinct transport cells characterized by net westward longshore sediment transport. Along eastern Dauphin Island, net longshore transport is eastward toward Mobile Pass.

Author: Davis, R. A., M. V. Fitzgerald, and J. Terry (1999)
Title: Turtle nesting on adjacent nourished beaches with different construction styles: Pinellas County, Florida
Source: *Journal of Coastal Research* **15**:111-120
Findings/Summary: Study of the effect of beach nourishment on sea turtle nesting. Key information was the comparison of beach compaction over time for one nourished beach that was tilled after nourishment with two un-tilled nourished beaches. The results were not that clear because of the high degree of temporal and spatial variability in the measurements. Tilling did initially reduce compaction, but compaction also decreased at one of the un-tilled comparison beaches. So, it was not clear to the authors whether the decrease in compaction was due to tilling, or other factors such as ground water and storm inundation. At 3 and 6 months post-tilling, the beach compaction was the same as prior to tilling.

Author: Dingler, J. R., S. A. Hsu, and T. E. Reiss (1992)
Title: Theoretical and measured aeolian sand transport on a barrier island, Louisiana, USA
Source: *Sedimentology* **39**:1031-1043

Findings/Summary: Measured and modeled aeolian sand transport during the passage of a 4-day cold front, followed by more seasonal southerly winds in February 1989. The north wind initially transported sand from the unvegetated backbeach to the upper beachface. However, the southerly wind returned the sand to the upper backbeach. Sand would be lost from the beach by wave erosion during different storm/wave conditions.

Author: Ellis, J. and G. W. Stone (2006)
Title: Numerical simulation of net longshore sediment transport and granulometry of surficial sediments along Chandeleur Island, Louisiana, USA
Source: *Marine Geology* **232**: 115-129
Findings/Summary: Study of the net longshore sediment transport system along the Chandeleur Island using the wave refraction model, WAVENRG, which provided estimates of the transport volumes and drift directions alongshore. The longshore transport system is characterized by a bidirectional drift system, with drift directed both north and south from a nodal point located in the south-central portion of the barrier island. Predicted rates were 87,000 m^3/yr for the southern cell and 63,000 m^3/yr for the northern cell.

Author: FDEP (Florida Department of Environmental Protection) (2010)
Title: Critically Eroded Beaches in Florida
Source: http://www.dep.state.fl.us/beaches/publications/tech-report.htm
Oil type: N/A
Findings/Summary: FDEP has the responsibility to identify those beaches of the state which are critically eroding and to develop and maintain a comprehensive long-term management plan for their restoration. In 1989, a first list of areas affected by erosion was developed based upon an abbreviated definition of critical erosion. That list was updated in 2010. This report provides a county-by-county listing and map of those beaches classified as critically eroding and non-critically eroding.

Author: Georgiou, I. Y., D. M. Fitzgerald, and G. W. Stone (2005)
Title: The impact of physical processes along the Louisiana coast
Source: *Journal of Coastal Research,* Special Issue No. **44**: 72-89
Findings/Summary: This article summarizes the more salient coastal processes that pertain to the Louisiana coast and discusses how these processes are affecting the barriers, tidal inlets, and backbarrier environments. The coast experiences low-energy waves having deepwater heights ranging from 0.5 to 1.0 meters and periods of 5 to 6 seconds. Eighty percent of waves approach from the south- east. Tides are mixed in western Louisiana and become diurnal in the central and eastern sectors. Cold fronts are significant geological agents, because they produce nearshore wave heights of 1 to 2 meters, they occur approximately 20 to 30 times a year, and they are responsible for reworking the bayside of barrier islands.

Author: Martinez, L., S. O'Brien, M. Bethel, S. Penland and M. Kulp (2009)
Title: Louisiana Barrier Island Comprehensive Monitoring Program (BICM). Volume 2: Shoreline Changes and Barrier Island Land Loss 1800s-2005
Source: University of New Orleans, LA. 32 pp
Findings/Summary: This study documents historical rate and range of Louisiana Gulf shoreline change for the period from 1855 to 2005 and provides a comprehensive quantification of

shoreline evolution trends along Louisiana's Gulf shoreline. Using historical maps, satellite imagery, and aerial photography, patterns and rates of shoreline change were documented for 4 time periods: 1855-2005 (historical term), 1920's-2005 (long term), 1996-2005 (short term), and 2004-2005 (near term). The high-water line was used as the official shoreline and was interpreted and determined on the aerial photography and satellite imagery according to the location of the wet and dry-beach contact or the high-water debris line. Measurements of shoreline movement and change were taken along transects perpendicular to an offshore baseline spaced at 50 meter intervals alongshore. The shoreline was divided into 80 reaches based on the geomorphology, coastal evolution trends, existence of man-made structures, and/or a combination of these factors. The average historical rate of shoreline change is -2.7 m/yr. The average long-term rate of shoreline change is -4.2 m/yr. During the last decade, shoreline change rates have accelerated to -8.2 m/yr. The impacts of Hurricanes Katrina and Rita in 2005 accelerated the near-term rate of erosion to -57.8 m/yr. The highest rates of erosion due to the 2005 storm impacts were found along the Mississippi River delta barrier islands of the Isle Derniers, Timbaliers, and Chandeleur Islands with some sectors undergoing over 182 meters of landward retreat.

Author: Miner, M. D., M. A. Kulp, D. M. Fitzgerald, J. Flocks, and H. D. Weathers (2009)
Title: Delta lobe degradation and hurricane impacts governing large scale coastal behavior, south-central Louisiana, USA
Source: *Geo-Marine Letters* **29**: 441-453
Findings/Summary: This study conducted single-beam bathymetric surveys along 165-km of the south-central Louisiana barrier coast, from Raccoon Point in Terrebonne Parish to Sandy Point in Plaquemines Parish in 2006. These data, combined with historical bathymetry from three time periods (dating to the 1880s), were used to generate a series of digital elevation models that were used to calculate sediment volumetric changes and determine long-term erosional-depositional trends. Key findings included an increase in tidal inlet cross-sectional area from ~41,400 m2 to ~139,500 m2, and that rates of shoreface erosion are an order of magnitude greater during active hurricane seasons compared to long-term trends.

Author: Morton, R. A. (2008)
Title: Historical changes in the Mississippi-Alabama Barrier-Island Chain and the roles of extreme storms, sea level, and human activities
Source: *Journal of Coastal Research* **24**: 1587-1600
Findings/Summary: This study was a historical analysis of a barrier-island chain in the north-central Gulf of Mexico showing that the Mississippi barrier islands and Dauphin Island, AL are undergoing rapid systematic land loss and translocation associated with: (1) unequal lateral transfer of sand related to greater updrift erosion compared to downdrift deposition; (2) barrier narrowing resulting from simultaneous erosion of shores along the Gulf and Mississippi Sound; and (3) barrier segmentation related to storm breaching. The principal causes of land loss are frequent intense storms, a relative rise in sea level, and a sediment-budget deficit caused in part by deepening of dredged channels across the outer bars.

Author: Nelson, D. A. (1987)
Title: Effect of the use of tilling to soften nourished beach sand consistency for nesting sea turtles

Source: US Army Engineer Waterways Experiment Station, Vicksburg, MS, MP-87, 18 pp.
Author: Nelson, D. A. and D. D. Dickerson (1988)
Title: Response of nesting sea turtles to tilling of compacted beaches, Jupiter Island, Florida
Source: Unpubl. report. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS. 26 pp.
Findings/Summary: Was not able to obtain copies of these two papers (unpublished). However, other sources said: Tilling of a nourished beach with a root rake may reduce the sand compaction to levels comparable to unnourished beaches. However, this pilot study showed that a tilled nourished beach will remain uncompacted for up to one year. Therefore, the USFWS requires multi-year beach compaction monitoring and, if necessary, tilling to ensure that project impacts on sea turtles are minimized.

Author: Owens, E. H., R. A. Davis Jr., J. Michel, and K. Stritzke (1995)
Title: Beach cleaning and the role of technical support in the 1993 Tampa Bay spill
Source: Proceedings International Oil Spill Conference, American Petroleum Institute, Washington, DC, Publication No. 4620, pp. 627-634
Findings/Summary: Paper describes the use of surf washing as a final polishing step for cleanup of oil during the Tampa Bay oil spill in 1993. Describes the decision-making process and trade-offs considered. Sand removal during the mechanical and manual treatment (prior to surf washing as a polishing step) was estimated to be 34,000 m^3. Beach profile surveys at 7 locations 1 week before and 1 week after the treatment was conducted showed net losses at 5 locations and net gains at 2 locations.

Author: Owens, E. H. (1998)
Title: Sediment relocation and tilling – underused and misunderstood techniques for the treatment of oiled beaches
Source: In: Proceedings 21st Arctic and Marine Oil Spill Programme (AMOP) Technical Seminar, Environment Canada, Ottawa, ON, pp. 857-872.
Findings/Summary: Summary of seven oil spills where surf washing (sediment relocation) and tilling have been used to speed the rate of oil removal from beaches. Describes each method, the objective, and conditions for optimum use.

Author: Rosati, J. D., M. R. Byrnes, M. B. Gravens, and S. F. Griffee (2007)
Title: Mississippi Coastal Improvement Project Study, Regional Sediment Budget for the Mississippi Mainland and Barrier Island Coasts
Source: U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal Hydraulics Laboratory, 183 pp.
Findings/Summary: Source for data for the Alabama-Mississippi barrier islands on the average significant wave heights in winter (0.6 m) and in summer (0.4 m).

Author: Rosati, J. D. and G. W. Stone (2009)
Title: Geomorphologic evolution of barrier islands along the northern U.S. Gulf of Mexico and implications for engineering design in barrier restoration
Source: *Journal of Coastal Research* **25**:8-22.

Findings/Summary: Literature review of northern Gulf of Mexico (Louisiana, Mississippi, Alabama, and Florida panhandle) barrier islands in terms of the processes and geomorphologic responses to storms, including Category 1-2 hurricanes. Provided data on longshore sediment transport rates for different islands: 50,000 to 100,000 m^3/y for East and West Grand Terre and approaching 65,000 m^3/y at West Ship Island and at Western Dauphin Island.

Author: Schmid, K. (2003b)
Title: Nearshore bar morphology with relationship to shoreline change on a renourished beach: Harrison County, MS
Source: Proc. Coastal Sediments '03, May 18-23, Clearwater Beach, FL
Findings/Summary: Abstract about a study of the nearshore bar morphology in Harrison County using aerial photographs from the 1970s to the middle 1990s. Bar types ranged from simple shore-parallel bars to multiple bar interfaces. Bar morphology categories and change through time were classified along the shoreline at 50 m intervals. Shoreline change was computed by comparing surveyed (GPS) mean high water (MHW) positions from 1993 and 2000. The shoreline change data was then added to the same 50 m intervals used in mapping bar types. Results from the western portion of the study area suggested that highly eroding areas are associated with a dominance of multiple sets of transverse bars (bars oriented at high angles to the shoreline) indicative of a bimodal longshore sediment transport regime. Areas that show little shoreline change and/or accretion tend to have multiple sets of low angle (shore-parallel) bars indicating low longshore transport. The overall bar morphology patterns in Harrison County have remained nearly constant in the past twenty years, even with several nourishments taking place. The author suggested that bar patterns are an inherent indicator of the dominant physical conditions and a powerful tool in understanding the sediment transport direction, and to some degree magnitude, at specific 'Hot Spots' along the shoreline.

Author: Stone, G. W. and F. W. Stappor, Jr. (1996).
Title: A nearshore sediment transport model for the northeast Gulf of Mexico coast, U.S.A.
Source: *Journal of Coastal Research* **12**(3):786-792.
Findings/Summary: They generated a sediment transport model for the 400 km-long stretch of coast along the northeastern Gulf of Mexico from Dog Island, FL, to Morgan Point, AL. The figures with the model estimates are shown below.

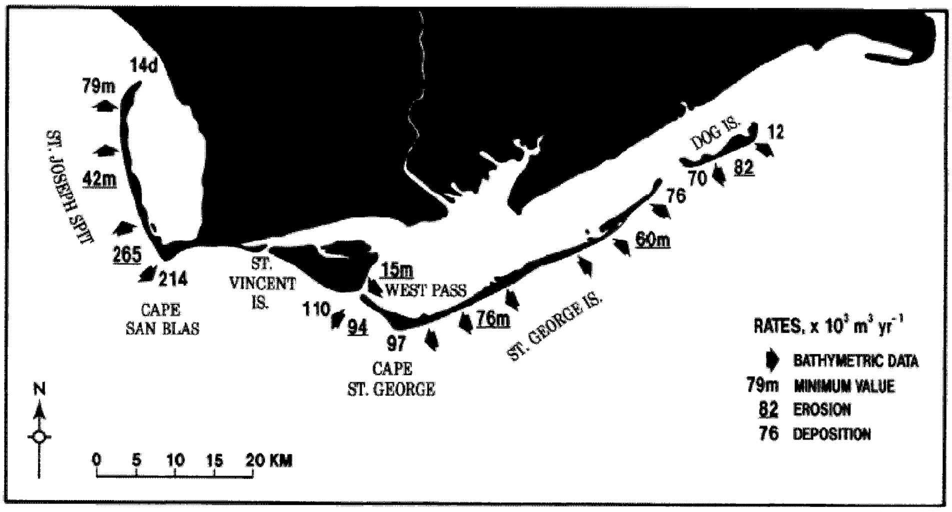

Figure 3. Sediment transport model for the Apalachicola Region. Transport rates are in m^3 yr^{-1} (modified from STAPOR, 1973a).

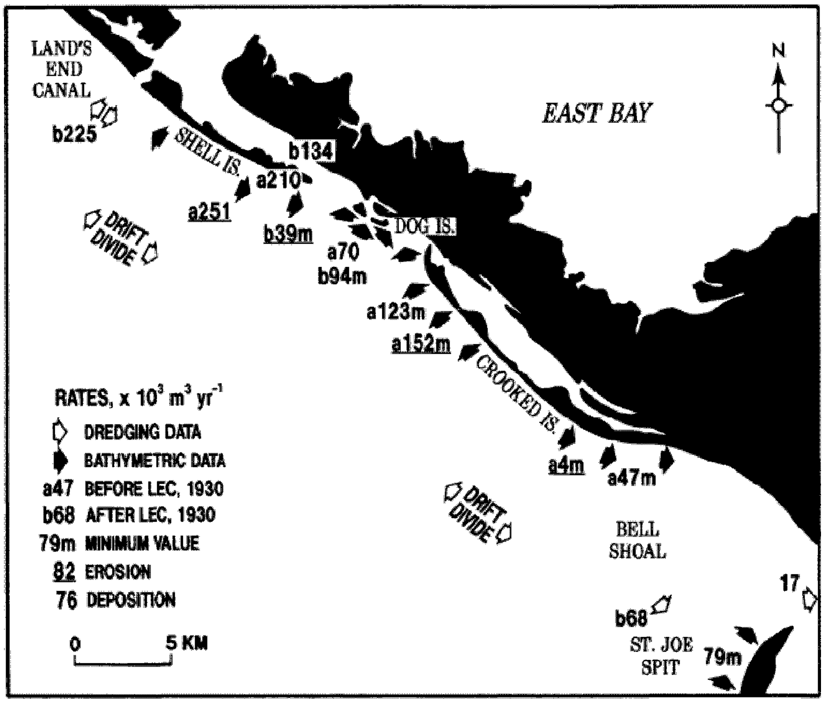

Figure 4. Sediment transport model for the Panama City Region. Transport rates are in m^3 yr^{-1} (modified from STAPOR, 1971).

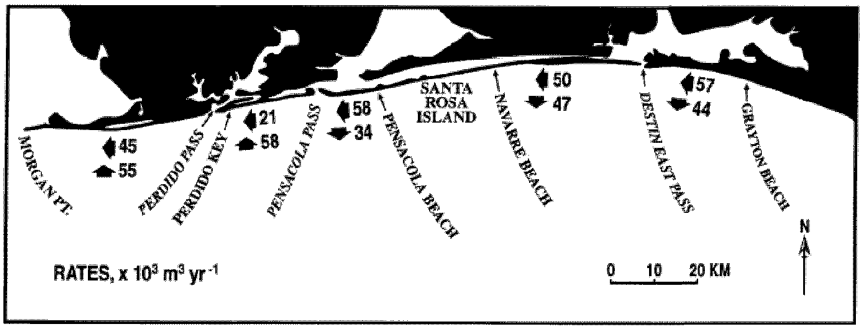

Figure 5. Sediment transport model for the Grayton Beach-Santa Rosa Island Region, and the Perdido Key-Morgan Peninsula Region. Transport rates are in $m^3\ yr^{-1}$.

Author: Williams, S. J., S. Penland, and A. Sallenger (1992)
Title: Louisiana Barrier Island Erosion Study: Atlas of Shoreline Changes from 1853 to 1989
Source: U.S. Geological Survey, Reston, VA. 108 pp.
Findings/Summary: Classic study of beach erosion on the Louisiana barrier islands with detailed figures and maps of the erosion rates and patterns for each of the Louisiana barrier island chains.

B. BIOLOGY, LIFE HISTORY

Author: Bilodeau, A. L. and R. P. Bourgeois (2004)
Title: Impact of Beach Restoration on the Deep-Burrowing Ghost Shrimp, *Callichirus islagrande*
Source: *Journal of Coastal Research* **20**(3): 931-936
Oil type: NA
Relevance/pertinence to Injury Assessment: This article describes a dominant sand beach invertebrate species on the barrier islands of the Isle Dernieres chain of Louisiana (East Island, Trinity Island, Grand Isle, Elmer's Island, New Cut, Whiskey Island, and Raccoon Island).
Methods: Following beach restoration on barrier islands, the authors compared sediment characteristics and recolonization of the ghost shrimp by sampling seven sites over a 2.5 year period. Two of the sites were impacted by beach renourishment activities and five of the sites were control sites.
Findings/Summary: Beach renourishment led to the elimination of the ghost shrimp from the intertidal zone. Recolonization of the island saw little or no recruitment of this species and may have been the result of poorly matched sediment types.

Author: Botton, M. L. and J. W. Ropes (1987)
Title: Populations of Horseshoe Crabs, *Limulus polyphemus*, on the Northwestern Atlantic Contintental Shelf
Source: *Fishery Bulletin* **85**(4): 805-812
Oil type: NA
Relevance/pertinence to Injury Assessment: This study provides information on the life span of the horseshoe crab along the Atlantic coast. Although not in our region of interest, the data may be applied to horseshoe crabs in the Gulf of Mexico as well.
Methods: The authors used bottom trawl and ocean clam surveys from the past 20 years to evaluate the distribution and abundance of horseshoe crabs on the Middle Atlantic continental shelf (North Carolina to southern New England).
Findings/Summary: Horseshoe crabs on the continental shelf were most abundant between Virginia and New Jersey (estimated at 2.3-4.5 million individuals). The number of crabs decreases on the shelf during the summer months (July-August) presumably due to the migration into the estuaries to spawn. The majority of animals were caught during spring and fall periods. Horseshoe crabs were found in depths of 290 m off of North Carolina at the edge of the continental shelf, where the continental slope is closer to the shore. This suggests that the distance from shore, and not depth, limits the dispersal of crabs.

Author: Bowman, M. L. and R. Dolan (1985)
Title: The Relationship of *Emerita talpoida* to Beach Characteristics
Source: *Journal of Coastal Research* **1**(2): 151-163
Oil type: NA
Relevance/pertinence to Injury Assessment: This article provided life history data for *Emerita talpoida*, a dominant sand beach invertebrate.
Methods: The authors examined the spatial and seasonal distribution of the mole crab by establishing 10 transects at 100 m intervals along an exposed sand beach of North Carolina. The transects were sampled from February to November.

Findings/Summary: The distribution of mole crabs over the beach face is largely influenced by wave energy, direction of wave approach, grain size, and beach slope. The greatest densities of *E. talpoida* occurred near the lower part of the beach, or step. This species rarely occurs in depths of sediments greater than 5 cm. An onshore migration of the overwintering population was observed in the spring with the highest densities occurring in the late summer and early fall.

Author: Britton, J.C. and B. Morton (1989)
Title: Shore Ecology of the Gulf of Mexico
Source: University of Texas Press, Austin, TX, 387 pp.
Oil type: NA
Relevance/pertinence to Injury Assessment: The authors include life history information (e.g., life span, timing of reproduction) for some of the dominant sand beach species (e.g., *Donax*, *Emerita*).
Methods: NA
Findings/Summary: This is a review of the ecology of hard shores, soft shores, subtidal sands, banks, and coral reefs in the Western Gulf of Mexico. The authors focus mainly on the area from Texas to the Yucatan. It provides an overview of the physical environment as well as the biota associated with each shore type.

Author: Curry, M. (2001)
Title: An Overview of the Ecology and Services of Large Burrowing Organisms with Consideration for Oil Spills in the United States
Source: Damage Assessment Center, National Oceanic and Atmospheric Administration
Oil type: Refined oils, crude oils
Relevance/pertinence to Injury Assessment: This paper describes large burrowing organisms found in the Northern Gulf of Mexico.
Methods: NA
Findings/Summary: The article provides information on large burrowing organisms in a natural resource damage assessment context. Information includes but is not limited to: physical and biological services provided, ecological characteristics (e.g., location along the beach face, depth of burial), sampling protocols, and oil impacts. The tables and information found in the appendices of the report have beneficial information to our injury assessment.

Author: Dahl, E. (1952)
Title: Some Aspects of the Ecology and Zonation of the Fauna on Sandy Beaches
Source: *Oikos* **4**: 1-27
Oil type: NA
Relevance/pertinence to Injury Assessment: This paper provides life history data for several dominant sand beach macrofauna.
Methods: The author summarizes the macrofauna found on six beaches among various locations (Chile, Venezuela, Magellan Strait, Sweden, and Norway).
Findings/Summary: The author divided sandy shores into three zones and summarized the macrofauna and their ecological characteristics within each zone. The zones include: the subterrestrial fringe, the midlittoral zone, and the sublittoral fringe. The subterrestrial fringe was inhabitated mainly by Talitrid amphipods and *Ocypodid* crabs. The midlittoral zone was comprised of Cirolaninae (isopods) and Haustoriid amphipods. The sublittoral zone was mainly

amphipods (Pseudalibrotus, Haustoriidae, Phoxocephalidae, and Oedocerotidae), as well as Decapod Crustacea.

Author: Defeo, O., A. McLachlan, D. S. Schoeman, T. A. Schlacher, J. Dugan, A. Jones, M. Lastra, and F. Scapini (2009)
Title: Threats to Sandy Beach Ecosystems: A Review
Source: *Estuarine, Coastal, and Shelf Science* **81**: 1-12
Oil type: NA
Relevance/pertinence to Injury Assessment: This review provides abundance and biomass data for sand beach ecosystems, as well as information on wrack removal and wrack-associated fauna.
Methods: NA
Findings/Summary: The authors review sand beaches and their ecology characteristics (e.g., physical attributes, faunal patterns). Common stressors that are discussed include: recreation, grooming, nourishment, pollution, exploitation (e.g., harvesting of fish), biological invasions (human induced), coastal development, mining, and climate change. Beaches appear to be most at risk from human population growth and development encroaching from the land side and erosion and climate change occurring on the water side.

Author: Dexter, D. (1972)
Title: Comparison of the Community Structures in a Pacific and an Atlantic Panamanian Sandy Beach
Source: *Bulletin of Marine Science* **22**(2): 449-462
Oil type: NA
Relevance/pertinence to Injury Assessment: This paper provided community metric data for Ancinus spp., a common sand beach polychaete.
Methods: Two beaches (Atlantic Coast, and Pacific Coast) were compared to evaluate faunal zonation, community structure, abundance, and species composition. Sampling procedures included placing a 0.1 m^2 quadrat on the substrate at low tide and removing the sediment to a depth of 5 cm.
Findings/Summary: The Pacific shoreline had 6 times the density of individuals, 9 times the biomass, and 3 times as many species than the Atlantic shoreline. Common species included *Cirolana mayana*, *Ancinus* spp., and nerinid polychaetes. The author suggests that the Pacific macrofauna may be better adapted to changing environmental features since the Pacific coast is exposed to greater variability. Atlantic macrofauna were more diverse in terms of equitability of species distribution. Density, biomass, and abundance estimates were provided for all species collected (see Table 1).

Author: Diaz, H. (1980)
Title: The Mole Crab *Emerita talpoida* (Say): A Case of Changing Life History Pattern
Source: *Ecological Monographs* **50**(4): 437-456
Oil type: NA
Relevance/pertinence to Injury Assessment: This paper provides life history data for the mole crab, *Emerita talpoida*, a dominant sand beach macroinvertebrate on sand beaches.
Methods: A two-year study at four sites along Bogue Banks, North Carolina was conducted to evaluate the population dynamics of the mole crab. At each site, 25 m transects were set parallel

to the water's edge and placed at 5 m intervals from low to high water. Four quadrats were taken at each transect at 6 m intervals. Two shovelfuls of sand were taken per quadrat and analyzed.
Findings/Summary: Aggregations of mole crabs were observed in spring and fall, with fewer aggregations observed in winter. Midsummer aggregations formed 5-10 m bands several kilometers long on the beach. Recruitment of new individuals occurred during the summer months, as did the mortality of many individuals of the adult population. Females were observed with eggs in the spring and summer months. Life span appeared to be within one year.

Author: Dolan, R., C. Donoghue, and D. Stewart (2006)
Title: Long-term Impacts of Tidal Inlet Bypassing on the Swash Zone Filter Feeder *Emerita talpoida*, Oregon Inlet and Pea Island, North Carolina
Source: *Shore and Beach* **74(1)**: 23-27
Oil type: NA
Relevance/pertinence to Injury Assessment: This paper describes the habitat and behavioral characteristics of the mole crab.
Methods: This was a 15 year monitoring study that used 44 beach transects to show physical and ecological changes associated with the dredging and beach nourishment on Pea Island National Wildlife Refuge (NWR).
Findings/Summary: The study showed a reduction in sand size and a reduction in mole crab numbers. Mole crabs burrow into wet sediment of the lower swash zone to feed and filter organic detritus and microorganisms from the wave backwash. The mortality of the mole crab from the sand bypassing from the dredged inlet to Pea Island NWR is a direct result of burial due to the large volumes of sand involved.

Author: Dugan, J. E., D. M. Hubbard, D. L. Martin, J. M. Engle, D. M. Richards, G. E. Davis, K. D. Lafferty, and R. F. Ambrose (2000)
Title: Macrofauna Communities of Exposed Sandy Beaches on the Southern California Mainland and Channel Islands
Source: Fifth California Islands Symposium, OCS Study, MMS 99-0038:339-346.
Oil type: NA
Relevance/pertinence to Injury Assessment: This paper describes the macrofauna associated with wrack stranded on sand beaches in California. The study provided estimates for wrack cover and volume along sand beaches.
Methods: Macrofauna along 36 beaches in southern California were monitored for species richness, abundance, and biomass. Physical characteristics of beaches and macrophyte wrack cover were also recorded.
Findings/Summary: The surveyed beaches were mainly modally reflective and intermediate morphodynamic types. Macrofauna richness was higher on mainland sand beaches than on island beaches. Species richness and abundance was positively correlated with wrack cover. Species richness, abundance, and biomass were lower on groomed beaches (i.e., beaches where wrack is regularly removed for aesthetic purposes) than ungroomed beaches.

Author: Dugan, J. E., D. M. Hubbard, M. D. McCrary, and M. O. Pierson (2003)
Title: The Response of Macrofauna Communities and Shorebirds to Macrophyte Wrack Subsidies on Exposed Sandy Beaches of Southern California
Source: *Estuarine Coastal and Shelf Sciences* **58(S)**: 133-148

Oil type: NA
Relevance/pertinence to Injury Assessment: This study provides data on the amount of wrack found on sand beaches as well as abundance data for wrack-associated species.
Methods: The authors evaluated 15 exposed sand beaches in southern California for macroinvertebrate species richness, abundance, and biomass. They also recorded abundance of shorebirds. The beaches examined were modally intermediate morphodynamic types, three of which were groomed.
Findings/Summary: These data suggest that wrack subsidies strongly influence macrofaunal communities on sand beaches. Wrack-associated macrofauna comprised >37% of the species on ungroomed beaches and 25% or more of the total abundance on half of the ungroomed beaches. The removal of wrack through regular grooming of the beach decreased the amount of food available for higher trophic levels (i.e., shorebirds) and reduced the species richness, abundance, and biomass of macrofauna.

Author: Dugan, J. E., D. M. Hubbard, H. M. Page, and J. P. Schimel (2011)
Title: Marine Macrophyte Wrack Inputs and Dissolved Nutrients in Beach Sands
Source: *Estuaries and Coasts* (in press)
Oil type: NA
Relevance/pertinence to Injury Assessment: This article provided data on the amount of wrack inputs, wrack cover, and standing crop of wrack found on southern California beaches.
Methods: Ten beaches that differed in proximity to kelp forests were surveyed along 3 transects for wrack inputs and cover. Porewater samples were collected from the 3 intertidal levels was analyzed for concentrations of nutrients.
Findings/Summary: This study evaluated the affect of macrophyte wrack on nearshore and intertidal nutrient cycling during the summer season. Intertidal dissolved organic nitrogen (DON) and dissolved organic nitrogen (DIN) were strongly correlated with wrack biomass. A net input rate for marine macrophyte wrack of 1.7 kg/m/day was estimated, yielding an estimated total net input of 620 kg/m/yr. The standing stock of marine macrophyte wrack varied significantly with mean values ranging from 0.41 to 46.43 kg/m. Mean concentrations of total DIN in intertidal pore water varied from 1 to 6,553 μM among beaches. The highest concentrations of DIN were found at the high tide line where wrack accumulates. Mean concentrations of DON in pore water also varied among beaches from 7 to 2,006 μM.

Author: Dworschak, P.C. (1998)
Title: Observations on the Biology of Burrowing Mud Shrimps *Callianassa tyrrhena* and *C. candida* (Decapoda: Thalassinidea)
Source: *Journal of Natural History* **32**: 1535-1548
Oil type: NA
Relevance/pertinence to Injury Assessment: This study provides data on the life span of *Callichirus* spp. (ghost shrimp), relevant to our dominant Louisiana sand beach species.
Methods: Ghost shrimp were collected from a silty fine-grained sand tidal flat in the Bay of Strunjan, Piran, Slovenia (Northern Adriatic Sea) and from a medium- to very fine-grained sand at Lido di Staranzano, Monfalcone, Italy to characterize growth parameters and population structure as well as parasitism in individuals.
Findings/Summary: The species studied here were found to have a life span of 4 years, although other studies have recorded between 2 and 4 years among the callianassids.

Recruitment of juveniles was observed in September and large animals were present year round. Sexual dimorphism was observed in both species.

Author: Engelhard, T. K. and K. Withers (1997)
Title: Biological Effects of Mechanical Beach Raking in the Upper Intertidal Zone on Padre Island National Seashore, Texas
Source: Padre Island National Seashore, National Park Service, Department of the Interior, Resource Management Division
Oil type: NA
Relevance/pertinence to Injury Assessment: This paper describes benthic and wrack associated organisms along a beach on Padre Island National Seashore. Although this is not one of our areas of interest, it is one of the few sources of information on wrack-associated macrofauna in the Northern Gulf of Mexico.
Methods: Four sites along a sand beach were sampled from May 1997 through September 1997 for two treatments (mechanical raking of wrack weekly, mechanical raking of wrack biweekly) and a control site. Species abundance and biomass were determined for macrofauna.
Findings/Summary: Both benthic organisms and wrack associated organisms were affected by mechanical raking to some degree. The authors found that macrofaunal density and biomass decreased as a result of the raking or to the vertical migration into the sand column in response to the disturbance caused by raking. This study identified the macrofaunal species typically associated with the benthic substrate versus those species associated with the wrack stranded in the upper intertidal zone.

Author: Felder, D. L. and R. B. Griffis (1994)
Title: Dominant Infaunal Communities at Risk in Shoreline Habitats: Burrowing Thalassinid Crustacea.
Source: OCS Study, MMS 94-0007, U.S. Dept of the Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office, New Orleans, LA, 87 pp.
Oil type: NA
Relevance/pertinence to Injury Assessment: This article describes the ecology of three species of ghost shrimp that are found in the Northern Gulf of Mexico.
Methods: The authors studied the populations of ghost shrimp from two sites: the estuarine shoreline of Bay St. Louis, Mississippi and the barrier island chain of Isle Dernieres, Louisiana. The species were monitored quarterly over a 2 year period.
Findings/Summary: The study shows the effects that burrowing ghost shrimp have on a large beach habitat with burrow densities and characteristics, and how these parameters have affected oil spill response and cleanup activities. Population dynamics such as density, biomass, age, and growth structure were recorded as well as burrow depths, surface areas, and volumes. The findings document baseline measures in healthy populations of ghost shrimp against which impacted populations may be compared.

Author: Filho, J. S. R., M. F. Almeida, and D. E. Aviz (2009)
Title: Spatial and Temporal Changes in the Benthic Fauna of a Macrotidal Amazon Sandy Beach, Ajuruteua, Brazil
Source: Journal of Coastal Research **56**: 1796-1780
Oil type: NA

Relevance/pertinence to Injury Assessment: This article provides community metrics for common intertidal polychaetes and wrack-associated species.
Methods: To evaluate benthic community structure, samples were collected every 2 months on four transects perpendicular to the shoreline in Brazil.
Findings/Summary: Density and richness tended to increase toward the lower intertidal zone and during the dry season. The dominant taxa found on this sand beach were Enchytraeidae, Gammaridea, *Scolelepis* sp. and *Dispio* sp. The study indicated the presence of three distinct intertidal zones (high, middle, and lower intertidal zones) and concluded that vertical faunal zonation is a result of biotic (morphological, behavioral, and adaptive characteristics) and abiotic factors (grain size, sediment moisture, wave exposure).

Author: Getter, C. D., G. I. Scott, and L. C. Thebeau (1981)
Title: Biological Studies
Source: The Ixtoc I Oil Spill. C.H. Hooper (Editor). U.S. Department of Commerce, NOAA Office of Marine Pollution Assessment. (Publication number 577-846-1982), 202 pp., U.S. Government Printing Office, pp. 119-174.
Oil type: Crude oil
Relevance/pertinence to Injury Assessment: This study provides abundance and life history data for several dominant macrofauna found along a Texas sand beach.
Methods: Monitoring of biological communities was conducted to assess changes and provide baseline data after the Ixtoc I oil spill along the Texas coast. The studies were conducted at inlets and lagoons, sand beaches, and near and offshore environments. Infaunal samples were taken with can grabs along a transect to characterize the macrofaunal communities on sand beaches.
Findings/Summary: A significant reduction in total population densities was recorded in the lower intertidal zone after the spill, including significant reductions of mole crabs and amphipods. The oil was not acutely toxic to beach fauna, although sublethal effects were found in mole crabs exposed to oil. Other factors, particularly storms, were not ruled out as the causes of such reductions.

Author: Gheskiere, T., V. Magda, P. Greet, and D. Steven (2006)
Title: Are Strandline Meiofaunal Assemblages Affected by a Once-Only Mechanical Beach Cleaning? Experimental Findings
Source: *Marine Environmental Research* **61**: 245-264
Oil type: NA
Relevance/pertinence to Injury Assessment: This study discusses the benefits and ecological services provided by wrack on sand beaches.
Methods: A before-and-after-control-impact (BACI) design was used on a Belgium sand beach to evaluate the effects of mechanical beach cleaning on the upper intertidal meiofaunal assemblages, mainly nematodes.
Findings/Summary: The authors describe the meiofaunal diversity of the wrack line and the effect and recovery of the assemblages after being exposed to a mechanical beach cleaner. A reduction in total abundance and a change in community structure were evident immediately after the beach cleaning. However, recovery occurred after the next high water phase.

Author: Hobbs, III, C.H., C. B. Landry, and J. E. Perry, III. (2008)

Title: Assessing Anthropogenic and Natural Impacts on Ghost Crabs (*Ocypode quadrata*) at Cape Hatteras National Seashore, North Carolina
Source: *Journal of Coastal Research* **24**(6): 1450-1458
Oil type: NA
Relevance/pertinence to Injury Assessment: This study provided life history and density data for *O. quadrata*, a common sand beach invertebrate on both Atlantic and Gulf coasts.
Methods: Authors surveyed four designated sites on two beaches in NC to assess the impact of off-road vehicles (ORVs) on the intertidal ghost crab. The four treatments included: a site with no ORV restrictions, a site where no ORVs were allowed, a site from which ORVs were to be restricted from the seaward ~20 m of the beach at all times, and a site from which ORV use on the seaward ~20 m of the beach was restricted from 2000 to 0600 hours.
Findings/Summary: Restricting ORV use on the beach crest 24 hours a day resulted in a significant increase in ghost crab mean burrow density. Significant increases were seen when ORV use was restricted from 2000 to 0600 hours. Burrow densities varied from 2 to 13 burrows per 100 m^2. However, more dramatic changes in population estimates were observed after high-energy storm events. After storms, crabs were able to repopulate areas where they their numbers had been reduced as a result of ORVs. Population dynamics may be temporarily influenced by ORVs and beach closures, however weather events appear to be more important in the long term.

Author: Irlandi, E. and B. Arnold (2008)
Title: Assessment of Nourishment Impacts to Beach Habitat Indicator Species
Source: Florida Fish and Wildlife Conservation Commission, Grant Agreement No. 05042, 126 pp.
Oil type: NA
Relevance/pertinence to Injury Assessment: This article describes the ecology of *Donax* species, *Emerita* species, and *Ocypode quadrata* (ghost crab) on the east and west coasts of Florida. Abundance, size, and burrow size were observed. This study provided information on the temporal distribution of species along the west coast of Florida.
Methods: Transects were used to measure physical parameters (e.g., sediment grain size, temperature, beach slope) and collect biological data pre- and post-nourishment of randomly selected beach sites on the east and west coasts of Florida. Upper, middle, and lower swash zones were sampled at ten sites.
Findings/Summary: The study quantified the temporal and spatial differences in abundance and size distributions of *Donax* spp., *Emerita*, and *O. quadrata*. The authors also quantified the effects of beach nourishment on these species. The abundance of *E. talpoida* and *Donax* spp. were highly variable so the study revealed no measurable impacts to these species from dune construction or nourishment projects for either coast. Burrow densities of *O. quadrata* were significantly reduced as a result of dune construction and beach nourishment projects. Recovery of ghost crab populations had not occurred after one year following the nourishment project.

Author: Juno, J., C. Castellanos, J. M. Vieitez, M. R. de la Huz, and M. Lastra (2005)
Title: The Macroinfauna of the Galician Sandy Beaches (NW Spain) Affected by the Prestige Oil-Spill.
Source: *Marine Pollution Bulletin* **50**: 526-536
Oil type: heavy fuel oil

Relevance/pertinence to Injury Assessment: This study provides abundance data for dominant sand beach macroinfauna, however the study is not in our region of interest.
Methods: The authors evaluated the effects of oiling on sand beach macroinfauna using a Before- and-After Impact study on 18 sand beaches. Species number, diversity, evenness, and dominance were calculated for every beach before and after the spill.
Findings/Summary: The study showed that several macroinvertebrates were reduced after the spill (*Eurydice*, *Scolelpis squamata*, nemerteans, and Diptera). The reduced abundance of these species appears to reflect the oiling and cleanup among these beach sites. Some rare species were eliminated completely. Diversity was not affected by oiling in this case.

Author: Keller, W. J. and C. M. Pomory (2008)
Title: Effects of Porous Mesh Groynes on Macroinvertebrates of a Sandy Beach, Santa Rosa Island, Florida, U.S.A.
Source: *Gulf of Mexico Science* **1**: 36-45
Oil type: NA
Relevance/pertinence to Injury Assessment: This paper describes the effects of habitat change on several invertebrate species typically found along the sand beaches of Florida's panhandle.
Methods: The authors sampled five groyne, intergroyne, and control transects for changes in invertebrate species 3 months after porous mess groynes were installed on a sand beach to prohibit erosion. The paper describes the changes in benthic macroinvertebrate abundance and diversity.
Findings/Summary: *Donax* (coquina clam), *Emerita* (mole crab), and several species of polychaetes were not eliminated as a result of the groyne installment. Burrowing polychaetes (*Arenicola cristata*) were most numerous in the groyne site compared to the intergroyne or control sites. No significant changes were observed with *Donax* or *Emerita* populations as seen in other beach nourishment studies, leading the authors to conclude that slow sediment accretion and similar sediment properties are a major factor in the survival of benthic macroinvertebrates. Porous mesh groynes do not significantly alter sand particle size; and the gradual accumulation of sand allows for species to adjust to the changing environment.

Author: Leber, K. M. (1982)
Title: Seasonality of macroinvertebrates on a temperate, high wave energy sandy beach.
Source: *Bulletin of Marine Science* **32**(1): 86-98.
Oil type: NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study evaluated the seasonal changes in macrobenthic community structure on a temperate, western Atlantic, high energy beach in North Carolina during a 15 month period (1976-1977). This paper described seasonal patterns, trophic relationships, and the degree of discreteness of the intertidal zone from adjacent communities.
Findings/Summary: Twelve species were collected from the intertidal and nearshore surf zones. Some of these species showed distinct seasonal patterns. *Emerita talpoida* and *Donax variabilis* were more abundant during warmer months at densities two to four orders of magnitude greater than other species, while haustoriid amphipods (*Haustorius* sp. and *Amphiporeia virginiana*) were dominant in winter. Tidal, vertical and nocturnal migrations were also evident in some species. Portunid and ocypodid crabs moved into the intertidal wash zone at night and fed on *Emerita talpoida*, *Donax variabilis* and *D. parvula*, which are an important link between

brachyuran crabs and fish, and beach top predators (shorebirds). While physical zones are distinct on the beach, the fauna were not precisely categorized.

Author: Lucrezi, S. and T.A. Schlacher (2010)
Title: Impacts of Off-Road Vehicles (ORVs) on Burrow Architecture of Ghost Crabs (Genus *Ocypode*) on Sandy Beaches
Source: *Environmental Management* **45**: 1352-1362
Oil type: NA
Relevance/pertinence to Injury Assessment: This Australian study provides some important behavioral and life history information on ghost crabs, a dominant sand beach macroinvertebrate.
Methods: Using transects from the base of the dune to the down-shore limit of burrow occurrence, ghost crab burrows were compared between sand beaches that were open to vehicles and beaches that were closed to vehicles. Burrow casts were made, removed, and analyzed for certain parameters including length, diameter, and weight.
Findings/Summary: The study found that vehicle traffic did influence the characteristics of ghost crab burrows. Deeper tunnels made by smaller crabs were found on vehicle-impacted beaches. Crabs began to change the architecture of the burrow and create a more simplified burrow shape after being heavily disturbed from vehicles.

Author: McLachlan, A., (1983)
Title: Sandy Beach Ecology: A Review.
Source: In: McLachlan A, Erasmus T (eds.) Sandy beach as ecosystems. W Junk, The Hague, p 321-380.
Oil type: NA
Relevance/pertinence to Injury Assessment: This article describes the sand beach environment and the characteristics that influence macrofaunal abundance and diversity.
Methods: NA
Findings/Summary: A review of sand beach ecology. Table 2 in the text provides abundance and dry biomass data for meiofauna. Table 3 provides mean abundance and dry biomass numbers for macrofauna across 105 beaches surveyed.

Author: McLachlan, A. (1985).
Title: The biomass of macro-and interstitial fauna on clean and wrack-covered beaches in Western Australia.
Source: *Estuarine, Coastal and Shelf Science* **21**(4): 587-599.
Oil type: NA
Relevance/pertinence to Injury Assessment: Low to Moderate
Methods: The benthic fauna was surveyed on two modally reflective, moderate energy beaches of Western Australian.
Findings/Summary: The more exposed beach did not have intertidal macrofauna and had a poor interstitial fauna, while the less exposed beach had a large deposit of wrack (161 kg m^{-1} dry mass). An amphipod species (*Allorchestes compressa*) comprised most of the macrofauna in fresh wrack. The total biomass of macrofauna, epifauna, meiofauna, protozoans, and bacteria on the wrack-covered beach was one to three orders of magnitude higher than on the more exposed beach. Dry biomass of macrofauna, epifauna, meiofauna, protozoans and bacteria was 160, 3, 112, 9 and 901 g/m on the wrack-covered beach, and 0, 0, 15, 4 and 180 g/m on the more

exposed beach. Meiofauna concentrated in the mid- to upper beach, protozoans near the surface and bacteria in the mid- to lower beach. This study indicated that production on sand beaches are strongly influenced by exposure gradients.

Author: McLachlan, A., A.C. Brown (2006)
Title: The Ecology of Sandy Shores, 2nd edition
Source: Academic Press, Elsevier, Burlington, MA, 373 pp.
Oil type: NA
Relevance/pertinence to Injury Assessment: The text provides a general overview on the biology of several sand beach macrofauna.
Methods: NA
Findings/Summary: A general overview describing sand beach habitats, the physical environment, the floral and faunal communities, food chains and nutrient cycling, and human impacts. It provides general ecology for sand beach macrofauna and meiofauna.

Author: McLachlan, A., A. De Ruyck and N. Hacking (1996).
Title: Community structure on sandy beaches: patterns of richness and zonation in relation to tide range and latitude.
Source: *Revista Chilena de Historia Natural* 69: 451-467.
Oil type: NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This paper compares species richness, abundance and biomass across different beach types, and assesses species richness between tropical and temperate beaches. This analysis was based on quantitative surveys of six Australian beaches within a range of wave and tide energy levels
Findings/Summary: Species richness is determined by the beach type and is controlled by physical factors (sand particle size, wave energy and tidal range). In this study, species richness increased from temperate microtidal to tropical macrotidal beaches, and although biomass values were extremely variable they fell within the recorded range. Differences were also observed in the zonation of common species between tropical and temperate beaches, with species in tropical beaches having a general downward shift on their distribution likely resulting from higher temperatures and greater desiccation of the sand on the upper shore. Higher species richness and diversity in macrotidal beaches may be the result of increased substrate stability, a more favorable environment dominated by tides, and the occurrence of species with semi-permanent burrows.

Author: McLachlan, A. and P. Hesp (1984).
Title: Faunal response to morphology and water circulation of a sandy beach with cusps.
Source: *Marine Ecology Progress Series* **19**(1): 133-144.
Oil type: NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This paper quantified the distribution of meiofauna, macrofauna, zooplankton and fishes in relation to beach features (cusp horns and bays areas in the cusp circulation, and rip currents).

Findings/Summary: Meiofauna were less dense on the cusp horn increased toward the cusp bay. While harpacticoid copepods had their lowest concentrations on the beach face and did not avoid the cusp horn, polychaetes and oligochaetes showed the opposite pattern. Macrofauna filter feeders and donacids concentrated in cusp bays and showed no tidal migrations. This distribution may be the result of sorting by the swash. Zooplankton, dominated by amphipods and mysids, was more abundant inside the surf zone, and had an even distribution between the cusp horn and the bay. The patters in species distributions are the result of differential water movement and variable size distribution which affect moisture, oxygen, water flow, food availability etc…

Author: Nelson, W.G. (1993)
Title: Beach Restoration in the Southeastern US: Environmental Effects and Biological Monitoring
Source: *Ocean and Coastal Management* **19**: 157-182
Oil type: NA
Relevance/pertinence to Injury Assessment: The author provides a summary of sand beach fauna from North Carolina to Mississippi.
Methods: This is an overview of studies that have been conducted in the region and provides recommendations and guidelines for completing beach restoration projects.
Findings/Summary: The paper describes the dominant fauna typically present within each beach zone and beach restoration impacts on the macrofaunal community. The majority of the paper describes recommended design and sampling considerations and methodologies.

Author: Peterson, M. S. and G. L. Waggy
Title: A Field Guide to Aquatic Habitats and Common Fauna of the Northern Gulf of Mexico: Chandeleur Islands, Louisiana to Perdido Key, Florida
Source: Unpublished
Oil type: NA
Relevance/pertinence to Injury Assessment: The authors list the common surf zone species for the Chandeleur Islands, Louisiana to Perdido Key, Florida.
Methods: NA
Findings/Summary: This grey literature is not extremely relevant to our study. The paper describes the facility and personnel at the Gulf Coast Research Laboratory in Ocean Springs, Mississippi. However, it does include species lists for offshore waters, bay waters, surf zone, oyster reefs, seagrass, and estuary habitats in the Northern Gulf of Mexico.

Author: Peterson, M. S., D. H. M. Hickerson, and G. G. Johnson (2000)
Title: Short-Term Consequences of Nourishment and Bulldozing on the Dominant Large Invertebrates of a Sandy Beach
Source: *Journal of Coastal Research* **16**(2): 368-378
Oil type: NA
Relevance/pertinence to Injury Assessment: This North Carolina study provides density data for *Donax* and *Emerita* species in the intertidal zone.
Methods: Sampling occurred on two nourished beaches and two control beaches during the summer months. Grain size, beach topography measurements, and other physical parameters were recorded. Transects were used to collect sediment samples to determine densities of the dominant macrofauna of the beach.

Findings/Summary: Nourishment and bulldozing activities were found to have a negative impact on sand beach macroinvertebrates. Densities of *Donax* and *Emerita* spp. were lower by 86-99% on nourished beaches than on control beaches 5 -10 weeks after the nourishment activities had ended. *Emerita* densities were lower by 35-37% three months after bulldozing activities had ended. Total *Donax* abundance was five times that of the control beaches. The number of ghost crab burrows on the upper 7 m of beach (newly formed dune face) were 55-65% lower on bulldozed beaches than on control beaches.

Author: Rakocinski, C. F., R. W. Heard, S. E. LeCroy, J. A. McLelland, and T. Simons (1994)
Title: Seaward Change and Zonation of the Sandy-Shore Macrofauna at Perdido Key, Florida, U.S.A.
Source: *Estuarine, Coastal and Shelf Science* **36**: 81-104
Oil type: NA
Relevance/pertinence to Injury Assessment: This article provided important life history data for several dominant sand beach invertebrates in the swash zone for the Florida Panhandle.
Methods: The authors sampled 36 stations along 4 transects in the month of October from the swash zone to 800 m seaward to characterize spatial community patterns of macrofauna. Species richness, total density, diversity, and composition were recorded.
Findings/Summary: This study recorded the macrofauna community from the swash zone to deeper offshore waters. Species richness and total density increased from the swash zone to the more seaward transects. The paper identified several environmental factors that determine the community structure on sand beaches including beach exposure, sediment grain-size, season, water temperature, salinity, and tidal zonation. Three common species dominated in the swash zone of Perdido Key: *Emerita talpoida*, *Scolelepis squamata*, and *Donax variabilis*. Table 2 in the paper provided detailed information on each species' trophic position, life mode, type of motility, reproductive mode, and relative body size.

Author: Rakocinski, C. F., R. W. Heard, T. Simons, and D. Gledhill (1991)
Title: Macroinvertebrate Associations from the Beaches of Selected Barrier Islands in the Northern Gulf of Mexico: Important Environmental Relationships
Source: *Bulletin of Marine Science* **48**(3): 689-701
Oil type: NA
Relevance/pertinence to Injury Assessment: This paper describes groups of infaunal and epifaunal invertebrates typically found along the sound and gulf sides of Horn Island, Ship Island, and Perdido Key in the Northern Gulf of Mexico.
Methods: Authors used a rotated Principal Component Analysis (PCA) to identify major faunal associations and describe relationships between those associations and environmental parameters.
Findings/Summary: This article provides a summary table (Table 8) of the faunal associations and their environmental relationships identified in the stepwise multiple regressions. Relationships include where on the beach face specific invertebrates are most likely to be found, the particular island location, protected versus exposed beach face, seasonal variability, salinities, and water temperatures.

Author: Rakocinski, C. F., S. E. LeCroy, J. A. McLelland and R. W. Heard (1995).

Title: *Macrobenthic inventory of the aquatic shoreline habitats within the Gulf Islands National Seashore. Final Report to the U.S. Dept. of the Interior.*
Source: Ocean Springs, MS. 248.
Oil type: NA
Relevance/pertinence to Injury Assessment: High
Methods: This study surveyed in 1993 the macrobenthic communities occupying sandy bottom habitats of the Gulf Islands National Seashore. Other habitats were also surveyed. Sites were located at West and East Ship, Hom and Petit Bois Islands in the Mississippi district, and Perdido Key, Santa Rosa Island, and Gulf Breeze in the Florida district
Findings/Summary: Species richness and diversity generally increased with seaward distance and were higher at protected than on exposed beaches. A higher numbers of taxa occurred more often in summer and fall. Mean density varied dramatically within and across seasons, and across seaward distances and sites. Dominant taxa included *Donax variabilis, Exosphaeroma diminutum, Haustorius jayneae, Lepidactylus* sp. A, *Metamysidopsis swifti, Paraonisfulgens, Scolelepis squamata, Sphaerosyllis taylori,* and unidentified oligochaetes. This paper highlights large spatial and temporal variability in species composition and abundance even across nearby sand beaches.

Author: Rakocinski, C. F., S. E. LeCroy, J.A. McLelland, and R. W. Heard (1998)
Title: Nested Spatiotemporal Scales of Variation in Sandy-Shore Macrobenthic Community Structure.
Source: *Bulletin of Marine Science* **63(2)**: 343-362
Oil type: NA
Relevance/pertinence to Injury Assessment: This paper provided important seasonal and life history characteristics for several sand beach invertebrates present on the barrier islands of the Gulf Islands National Seashore (Mississippi and Florida Panhandle).
Methods: Seventeen sand beach sites were sampled, seven sampled quarterly; ten sampled semi-annually. Infaunal and epifaunal macroinvertebrates were sampled from the upper 20-25 cm of sediment in the swash zone and in the subtidal zone. Historical data collected from some of these same sites were used for comparison.
Findings/Summary: Species richness, macrobenthic diversity, and macrobenthic density increased from the swash zone to the subtidal zone and were higher among protected beaches than exposed beaches. Total densities in the swash zones ranged from 172 to 503 per m^2. Tables 1-3 list the dominant and subdominant taxa and their occurrence by season for each exposed and protected sand beach site sampled.

Author: Rakocinski, C. F., S. E. LeCroy, J. A. McLelland and R. W. Heard (1998).
Title: *Macrobenthic effects of hurricanes Opal and Erin within the Gulf Islands National Seashore.*
Source: *Final Report to the U.S. Dept. of the Interior*. Ocean Springs, MS. 67.
Oil type: NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This report summarized the impacts of two hurricanes on the macrobenthic communities of sand beaches from the Gulf Islands National Seashore
Findings/Summary: The macrobenthic community of the swash zone appeared to have recovered within the year following the hurricane disturbances. Mean density among swash

zones was highly variable between 1993 and 1996 at exposed and protected beaches. Total geometric mean densities of exposed swash zones were 98-1,374 m^2 in 1993 and 226-1,116 m^2 in 1996, and densities of protected swash zones were 1,197-10,658 m^2 in 1993 and 449-13,320 m^2 in 1996. Protected beaches not only had higher densities, but also had a more diverse macrofauna community. The swash zones of protected beaches also had a greater variability in community structure compared to exposed beaches.

Author: Schlacher, T. A., R. de Jager, and T. Nielsen (2011)
Title: Vegetation and Ghost Crabs in Coastal Dunes as Indicators of Putative Stressors from Tourism
Source: *Ecological Indicators* **11**: 284-294
Oil type: NA
Relevance/pertinence to Injury Assessment: This paper provides density data for *Ocypode cordimama* (ghost crab). However, this is a different species than the ghost crab that occurs in the Gulf of Mexico and this study takes place in Australia. This paper should be used to supplement data only if density data for the Gulf of Mexico species are not available.
Methods: The authors sampled 22 sites along the fore dunes of a sandy beach. At each site, 5 cross-shore transects were used that extended from the unvegetated beach 3 m seaward from the base of the fore dune to the edge of the vegetation line (boundary between fore dune and the primary dune). Ghost crab burrows were counted and measured in 2 m x 1 m frames, the vegetation community was assessed, and physical parameters were recorded.
Findings/Summary: The study evaluated the impact of dune camping on the vegetation and ghost crabs in the fore dunes of a sand beach in Australia. It was determined that ghost crabs were attracted to the fore dunes that abutted camping sites, based on the distribution pattern of burrows across the dune field and body condition. The study assumed the increase in body condition was a result of food scraps left from campers. Minor effects were found on fore dune vegetation near camp zones but no widespread changes were noted.

Author: Shelton, C. R. and P. B. Robertson (1981)
Title: Community Structure of Intertidal Macrofauna of Two Surf-Exposed Texas Sandy Beaches
Source: *Bulletin of Marine Science* **31**(4): 833-842
Oil type: NA
Relevance/pertinence to Injury Assessment: Provides abundance, biomass, and density for some dominant sand beach invertebrates along the Texas coastline (*Donax, Emerita*, amphipods).
Methods: Two beaches (mainland and barrier island) along the Texas coast were surveyed bimonthly for intertidal macrofauna to collect biomass, abundance, diversity, zonation, and seasonal changes. Samples were taken by shoveling out sand to a depth of 10 cm within a 1/16 m^2 quadrat along a transect. Replicates were combined to give a 1/8 m^2 sample.
Findings/Summary: Haustoriid amphipods, Donax sp., and polychaetes (*Scolelepis squamata* and *Lumbrineris impatients*) were the numerically dominant species found at both beaches. Density and biomass were greater at the barrier island beach that was characterized with greater wave energy and more uniformly well-sorted sand. Diversity and richness were higher at the mainland beach. The mean density found at these sites ranged from 1,398/m^2 (mainland beach) to 3,980/m^2 (barrier island). The number of species found in the total area sampled (12.1 and

12.9 m^2) was 34 (barrier island) to 40 (mainland beach), respectively. Mean biomass density was recorded at 5.23 g/m^2 (mainland beach) to 28.74 g/m^2 (barrier island).

Author: Souza, J. R. B., and N. M. Gianuca (1995)
Title: Zonation and Seasonal Variation of the Intertidal Macrofauna on a Sandy Beach of Paraňa State, Brazil
Source: *Scientia Marina* **59**(2): 103-111
Oil type: NA
Relevance/pertinence to Injury Assessment: This paper provided life history data for *Scolelpsis squamata*. Although the study was conducted in Brazil, life history parameters may be used for this species that is also a dominant organism on Gulf of Mexico sand beaches.
Methods: Monthly sampling of intertidal macrofauna was conducted on a semi-tropical exposed sand beach in Barrancos, Parana State (SE Brazil). Species number, diversity, and evenness were determined and the physical parameters of the beach were documented.
Findings/Summary: The total number of organisms collected from the 55 m^2 sampling area was 16,179. The mean abundance was 22,845 individuals/m^2. *Scolelepis squamata* was among the top five most abundant species, dominant in the summer and fall in Brazil. The authors found the intertidal area to be divided into four zones based on macrofauna and three zones based on moisture. The number of species increased from high to low tide, and biomass was highest in the lower zone of the beach.

Author: Strasser, K. M. and D. L. Felder (1999)
Title: Sand as a Stimulus for Settlement in the Ghost Shrimp *Callichirus major* (Say) and *C. islagrande* (Schmitt) (Crustacea: Decapoda: Thalassinidea)
Source: *Journal of Experimental Marine Biology and Ecology* **239**: 211-222
Oil type: NA
Relevance/pertinence to Injury Assessment: This paper describes the seasonality of a species typically found along exposed sand beaches of Louisiana, *C. islagrande*.
Methods: Two experiments were conducted with *Callichirus* species taken from barrier islands in Louisiana**:** 1) larvae and postlarvae of *Callichirus major* and *C. islagrande* were treated with combusted sand to determine if removal of organic compounds triggered settlement similarly to natural sands, and 2) *C. major* postlarvae received different treatments to determine which characteristics of sand triggered burrowing (e.g., natural sand, no sand, combusted sand, combusted sand conditioned by seawater, combusted sand manipulated by adults, and autoclaved sand).
Findings/Summary: This study showed that larvae appear to be influenced to burrow from inorganic compounds whereas postlarvae are triggered by organic compounds. *C. major* larvae burrowed significantly less in combusted sand than natural sand whereas postlarvae of *C. islagrande* burrowed in both sand types. Combusted sand provided less of a stimulus to *C. major* postlarvae to burrow.

Author: Strasser, K. M. and D. L. Felder (2000)
Title: Larval Development of the Ghost Shrimp *Callichirus islagrande* (Decapoda: Thalassinidea: Callianassidae) Under Laboratory Conditions
Source: *Journal of Crustacean Biology* **20**(1): 100-117
Oil type: NA

Relevance/pertinence to Injury Assessment: This paper describes the ecology of a species typically found along sand beaches of Louisiana.
Methods: This article describes the zoeal and decapodid stages and reports the number and duration of larval stages of *Callichirus islagrande* based on laboratory cultures.
Findings/Summary: This species is endemic to the Gulf of Mexico and typically found in low to high intertidal habitats on barrier islands. This paper is not completely relevant to our injury assessment but does include some helpful information on one of the endemic sand beach species in our region of interest.

Author: Thebeau, L. C., J. W. Tunnell, Jr., Q. R. Dokken, M. E. Kindinger (1981)
Title: Effects of the Ixtoc I Oil Spill on the Intertidal and Subtidal Infaunal Populations Along Lower Texas Coast Barrier Island Beaches
Source: 1981 International Oil Spill Conference: 467-475
Oil type: heavy crude
Relevance/pertinence to Injury Assessment: This study provides abundance data for several dominant macrofauna in the northwestern Gulf of Mexico.
Methods: Before oil came ashore onto Texas sand beaches, researchers sampled intertidal and subtidal infauna to have baseline data available for comparison to post-spill surveys (sampled 1 month after the spill). Species composition and abundance were compared using 52 species of macroinfauna.
Findings/Summary: Four out of seven transects showed a decrease of at least 50% in total population densities between pre- and post-spill sampling periods. The number of species in the intertidal and subtidal communities did not show significant changes between pre- and post-spill sampling.

Author: Walls, E. A., J. Berkson, and S. A. Smith (2002)
Title: The Horseshoe Crab, Limuls polyphemus: 200 Millions Years of Existence, 100 Years of Study
Source: *Reviews in Fisheries Science* **10**(1): 39-73
Oil type: NA
Relevance/pertinence to Injury Assessment: This review provides life history and ecological characteristics for the horseshoe crab.
Methods: NA
Findings/Summary: This is a general overview of the biology, life history, and ecology of the horseshoe crab. The authors discuss the economic role the horseshoe crab has on commercial fishing, biomedical industries, and shorebirds. The article also reviews the mangement policies that are currently in place.

Author: Williams, A., R. Feagin, and A. W. Stafford (2008)
Title: Environmental Impacts of Beach Raking of *Sargassum* spp. on Galveston Island, TX
Source: *Shore and Beach* **76**: 63-69
Oil type: NA
Relevance/pertinence to Injury Assessment: This study provided information and biomass values for stranded wrack along the Texas coast as well as ecological information on wrack-associated species.

Methods: This study compared changes in elevation at raked and unraked beaches on Galveston Island, TX and recorded bird and macrofaunal species that use and inhabit the stranded wrack.
Findings/Summary: Elevation changes between raked and unraked beaches were not significant over a one year time. Several bird species were seen using the wrack and include laughing gull, willet, boat-tailed grackle, and least terns. The primary contributor to macrofauna biomass within the wrack was the beach-endemic amphipod, *Orchestia* spp. The pelagic gastropod, *Litiopa melanostoma*, dominanted numerically.

Author: Wilson, J. G. (1999)
Title: Population Dynamics and Energy Budget for a Population of *Donax variabilis* (Say) on an Exposed South Carolina Beach
Source: *Journal of Experimental Marine Biology and Ecology* **239**: 61-83
Oil type: NA
Relevance/pertinence to Injury Assessment: This study provides important life history data (i.e., life span, biomass, habitat requirements) for *Donax variabilis*, one of the dominant macrofauna on exposed sand beaches in the southeastern U.S.
Methods: Monthly core samples were collected at 10 m intervals using a transect running from the high tide line to the low tide line. Population density, biomass, and energy inputs as well as other life history parameters were estimated from the samples.
Findings/Summary: The highest density recorded for this species was 12,000 individuals/m^2 occurring during a spring spawning event. During this time, animals were mainly observed in a narrow band at the mid-tide level. Following spawning, the population nearly disappeared from the beach until later in the year when recruitment was assumed to have begun.

Author: Woodin, S. A., S. M. Lindsay, and D. S. Wethey (1995)
Title: Process-Specific Recruitment Cues in Marine Sedimentary Systems
Source: *Biological Bulletin* **189**: 49-58
Oil type: NA
Relevance/pertinence to Injury Assessment: This study provides life history data for *Arenicola cristata* (lugworm polychaete).
Methods: Juveniles of bivalves and polychaetes were collected and exposed to simulated erosional and mixing events. Burrowing behavior and timing were observed. Disturbances were defined as those that covered the original surface of sediment or removed at least 3-5 mm of sediment vertically.
Findings/Summary: The study found that juvenile infauna use cues from sediments to determine suitability for burrowing. The percentage of individuals that did not burrow increased significantly among disturbed sediments. The study supports the hypothesis that juveniles will reject sediments that have been disturbed when the disturbance is less than several hours old. The choice to burrow in sediments was made within 30 seconds.

C. Biological Effects from Oil and Oil Spills

Author: Ansari and Ingole 2002
Title: Effect of an Oil Spill from *MV Sea Transporter* on Intertidal Meiofauna at Goa, India.
Source: *Marine Pollution Bulletin* **44**(5): 396-402
Oil type/Oiling condition: Fuel oil; oiling conditions not reported
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study evaluated the effects of a fuel spill on the meiofauna community days after the spill.
Endpoints: Harpacticoid copepod and nematode density, index of nematode trophic diversity, and total petroleum hydrocarbons (TPH)
Findings: Total petroleum hydrocarbons in sediments a day after the spill reached 216±30 µg/g dw, declining steadily to 13±4 µg/g dw five weeks after the spill. These values were high relative to pre-spill values (0.43±0.16 µg/g dw). This spill caused short-term reduction in the density of dominant taxa, including copepods and nematodes, with nematodes recovering quicker than copepods. Total meiofauna density in the area most heavily impacted by the spill was relatively low compared to nearby beaches, indicating localized effects. Nematode to copepod ratios were high immediately after the spill, and remained elevated for the following three months. Recovery of the meiofauna community (i.e., low nematode to copepod ratios) was correlated with the reduction of TPHs in sediments, as well as with more favorable conditions post-monsoon season. The spill apparently did not have any effects on the index of nematode trophic diversity, and minimal to no long-term effects on the meiofauna community were noted. The effects of the oil spill on the meiofauna community were confounded by the seasonal monsoons and beach dynamics.

Author: AURIS Environmental (1995)
Title: *Scoping evaluation of the biological recovery of Mangroves, Coral Reefs, Seagrasses and Sedimentary Shores*
Source: A report by AURIS Environmental
Oil type: Various types
Relevance/pertinence to Injury Assessment: High
Methods: This report synthesized the state of knowledge on the effects of oil spills on several shoreline habitats, as well as the reported recovery times.
Findings/Summary: This report indicated that coarse grained and sandy shores recover quicker (0.5-5 years) than sheltered shorelines, seagrasses (0.5-50 years), coral reefs (10-100 years) and mangroves (5-100 years). Moderately treated tropical sandy beaches recovered within 5 months to 2 years, while untreated beaches recovered within 5 years. More exposed temperate beaches recovered quicker from an oil spill (within 6 years) than sheltered fine sandy beaches (>7 years). For selected case studies, recovery took longer than 5 years regardless of the climatic zone. Overall, treatment has a positive effect.

Author: Barron *et al.* 1999
Title: Sensitivity of the Sand Crab *Emerita analoga* to a Weathered Oil.
Source: *Bulletin of Environmental Contamination and Toxicology* **62**(4): 469-475
Oil type/Oiling condition: Crude oil; NA

Relevance/pertinence to Injury Assessment: Low to Moderate
Methods: This study determined the toxicity of water accommodated fractions (WAF) from field-collected weathered middle distillate oil to early life stages of the sand crab (*Emerita analoga*).
Endpoints: No observed (NOEC) and lowest observed (LOEC) effect concentrations for survival to day 6, growth, emergence, and molting, and concentrations causing 50% and 20% mortality (LC50s and LC20, respectively)
Findings: Total petroleum hydrocarbon concentrations ranged from <0.05 mg/L in controls to 6 mg/L in the higher WAF treatment (40% dilution). Mortality increased with increasing test concentration, and occurred sooner at higher TPH concentrations. The 6-day survival LC20 and LC50 values were 3.5 and 7.1 mg/L TPH, respectively, with a 96-hour LC50 estimated at 7.7 mg/L TPH. Growth was significantly reduced at 3.4 mg/L TPH, and the estimated EC20 and EC50 growth effects concentrations were 0.65 and 1.2 mg/L TPH, respectively. Emergence and molting were not statically significantly different between WAF treatments and controls.

Author: Barth 2002
Title: The 1991 Gulf War Oil Spill: Its Ecological Effects and Recovery Rates of Intertidal Ecosystems at the Saudi Arabian Gulf Coast - Results of a 10-Year Monitoring Period.
Source: *University of Regensburg, Regensburg, Germany*: 270
Oil type/Oiling condition: Crude oil; Heavy
Relevance/pertinence to Injury Assessment: High
Methods: This study summarizes the results of the first four years after the 1991 Gulf War oil spills and the monitoring that took place between 1995 and 2001. Only discussions related to sand beaches are presented here.
Endpoints: NA
Findings: The most conspicuous inhabitant of higher energy sand beaches is the ocypodid ghost crab, *Ocypode rodundata*. Other important components of the beach community include the deposit-feeding crab, *Scopimera crabicauda*, polychaetes and gastropods. High abundance of r-strategists species (polychaete *Owenia* spp. and two bivalve species) dominated the lower intertidal assemblage four years after the spills. In 2001, some oiled areas beneath clean sand did not have any fauna, while other oiled areas were characterized by the presence of polychaetes. The lower shore had the highest species abundance and diversity. Areas with favorable conditions for oil biodegradation recovered within 5 years of the spills. By 2001, high-energy sand beaches showed complete recovery (80% of the total impacted sand beaches), while low energy beaches were on their way to complete recovery 10 years after the spills.

Author: Beiras and Saco-Alvarez 2006
Title: Toxicity of Seawater and Sand Affected by the *Prestige* Fuel-Oil Spill Using Bivalve and Sea Urchin Embryogenesis Bioassays.
Source: *Water, Air, & Soil Pollution* **177**(1): 457-466
Oil type/Oiling condition: Heavy fuel oil; highly oiled
Relevance/pertinence to Injury Assessment: Low; may provide useful information on residual oil toxicity.
Methods: Bivalve and sea urchin toxicity and embryogenesis bioassays were conducted using seawater and sand elutriates collected from the top 4 cm surface layer of intertidal sediments.

Endpoints: Toxicity to invertebrate larvae
Findings: Sand elutriates did not show clear patterns of toxicity to either oyster or clam larvae, and inhibition of embryogenesis was only found in one test with undiluted sand. Surface water showed high toxicity to invertebrate larvae, and caused a significant reduction in embryo-larval length (≥50% compared to controls) even after 32-fold dilution with control seawater. A similar embryogenesis bioassays with water elutriates collected three months post-impact did not show toxicity, and the larvae obtained were similar in size to control. Hydrocarbon concentration in sand ranged between 0.8 and 2µg/g dry weight chrysene equivalents, while in water, hydrocarbon concentrations reached thousands of µg/L chrysene equivalents post-impact, decreasing to levels <1 µg/L six months later.

Author: Blaylock and Houghton 1989
Title: Infaunal Recovery at Ediz Hook Following the *Arco Anchorage* Oil Spill.
Source: *1989 Oil Spill Conference*
Oil type/Oiling condition: Crude oil; heavy oiling
Relevance/pertinence to Injury Assessment: High
Methods: This study surveyed over 18-months the recovery of benthic infauna from the *Arco Anchorage* oil spill and the subsequent beach cleanup.
Endpoints: Analysis of the infaunal (i.e., bivalve, crustaceans, and polychaetes) assemblage at different tidal elevations within beach transects. Specific endpoints included density, biomass, diversity, and number of species.
Findings: The 1985 *Arco Anchorage* crude oil spill impacted sections of the sheltered shore of Ediz Hook, WA, penetrating sand and gravel sediments of the intertidal zone. The combined effects of heavy oiling and beach cleanup activities caused near complete mortality of the infaunal community occurring at the most heavily oiled transects. Eight to nine months after the spill, the infaunal composition at heavily oiled stations was dominated by oligochaetes and nematodes. Later during the surveys other groups (i.e., polychaetes) increased in abundances and biomass. These heavily oiled transects had generally less diverse infaunal populations, but had also been impacted by industrial activities. Abundance and biomass of polychaetes and bivalves were relatively constant at the reference station, but increased over time at several heavily oiled stations. Biomass, density, and number of species had significant negative correlations with sediment hydrocarbon concentration. Bivalves were nearly absent from samples taken at heavily oiled and cleaned up areas, followed by their re-emergence ten months after the spill. This study concluded that the benthic infauna community likely resembled pre-spill conditions two years after the spill, however, the ongoing industrial activities may have hindered their recovery. A related study (Word *et al,*. 1987), indicated that sediments background hydrocarbon levels would take 18.5 months following the spill, and nearly four years for complete biological recovery of the benthos.
See: Word *et al.* 1987

Author: Bodin 1988
Title: Results of Ecological Monitoring of Three Beaches Polluted by the *Amoco Cadiz* Oil Spill: Development of Meiofauna from 1978 to 1984.
Source: *Marine Ecology Progress Series* **42**(2): 105-123
Oil type/Oiling condition: Crude oil; oiling conditions not reported
Relevance/pertinence to Injury Assessment: Moderate to High

Methods: The meiofauna community (primarily Nematoda and Copepoda) from the intertidal zone of 3 sand beaches was monitored over 6 years after the 1978 *Amoco Cadiz* spill, Brittany, France.
Endpoints: Copepod and nematode abundance, and copepod species richness and community structure
Findings: Two phases were noted: degradation and recovery. Time periods of both phases depended on the exposure of the beach and the taxon under consideration. The degradation phase resulted in a drastic quantitative and qualitative change of the meiofauna community, with effects lasting two years and three years for nematodes and copepods (i.e., reduced species richness), respectively. During this phase, the original populations were replaced by opportunistic fauna, likely less sensitive to the direct effects of hydrocarbon and dispersant toxicity and more tolerant of oxygen depletion in sediments. The recovery phase to "normal" conditions appeared to occur between 3 and 5 years after the spill. High energy exposed beaches likely experienced shorter recovery times than more sheltered sites. None of these three areas appeared to be subject to cleaning measures.

Author: Boucher 1980
Title: Impact of *Amoco Cadiz* Oil Spill on Intertidal and Sublittoral Meiofauna.
Source: *Marine Pollution Bulletin* 11(4): 95-101
Oil type/Oiling condition: Light crude; heavy oiling
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study documented the changes in the density of nematode and harpacticoid copepods from a fine-grained sand beach impacted by the *Amoco Cadiz* oil spill. Only discussions of the intertidal meiofauna are presented here.
Endpoints: Meiofauna density
Findings: The sand column remained oiled for several months even after the cleanup activities of the upper beach zone. The amount of oil decreased during the first three months after the spill before stabilizing at 100 µg/L. Prior to the spill, nematodes dominated the intertidal meiofauna community (88-97%), which decreased during the first two months after the spill to 58% of the initial density. Their density remained depressed for several months even after the occurrence of the natural spring bloom. The density of copepods on the other hand, remained relatively low for seven months after the spill.

Author: Castellanos *et al.* 2007
Title: A Four Year Study of Beach Macroinfauna after the *Prestige* Oil-Spill.
Source: *SYMPOSIUM on Marine Accidental Oil Spills*
Oil type/Oiling condition: Heavy fuel oil; several degrees of oiling
Relevance/pertinence to Injury Assessment: Moderate
Methods: Eighteen sand beaches were sampled along the Galician coast (NW Spain) six, eighteen, thirty, and forty two months after the 2002 *Prestige* oil-spill.
Endpoints: Abundance and composition of the macroinfauna community.
Findings: The most affected beaches were the located in La Coruña province, whereas those of Pontevedra and Lugo provinces were relatively unimpacted. In these beaches, the macroinfauna community was dominated by crustaceans (i.e., amphipods *Pontocrates arenarius* and *Talitrus saltator*, the isopod genus *Eurydice*) and polychaetes (i.e., polychaete genus *Scolelepis*). The number of species was lower in 2003, increased in 2004, and slightly decreased in 2005. Rare

species were eliminated in 2003 and reappeared in 2004, with some species disappearing again in 2005. Macroinfaunal abundance was low in 2003, except for the amphipod *P. arenarius* which reached high densities six months after the spill and throughout 2004. The polychaete *Scolelepis mesnili* and the isopod of the genus *Eurydice* reached their highest densities in 2005.

Author: Chan 1976
Title: Oil Pollution and Tropical Littoral Communities: Biological Effects of the 1975 Florida Keys Oil Spill.
Source: *University of Miami, Rosenstiel School of Marine and Atmospheric Science*
Oil type/Oiling condition: Crude oil; light to heavy oiling
Relevance/pertinence to Injury Assessment: Moderate
Methods: Periodic visits to impacted areas and recovery comparisons relative to unoiled sites. Repetitive stations were selected for long-term studies from one year after the oil came ashore to the return to pre-spill conditions. This study focused on several habitats, but only impacts on sand intertidal beaches are described here.
Endpoints: Abundance of the intertidal biota (amphipods and crabs)
Findings: Heavily oiled seagrass debris (<30 cm deep) covered the sandy upper littoral region and caused penetration of oil into the sand substrate. Although some of this debris was removed, oil continued to leach from the remnant debris, permeating the sand substrate to a depth of 10 cm. A month after the spill, the oil on sheltered beaches formed a hard, tarry layer of sand and waxy residue over the oiled sand, with fluid oil beneath the crust. Organisms were not found in the oiled grass or in the oil-soaked sand. Amphipods (possibly *Orchestia* spp.) and crabs (*Pachygrapsus transversus* and *Cyclograpsus integer*) were found associated with clean sea grass in the upper littoral two months after the spill. Six months after the spill, no oily debris was found, and the macrofauna abundance was similar to that of a control beach.

Author: Clifton *et al.* 1984
Title: Spilled Oil and Infaunal Activity- Modification of Burrowing Behavior and Redistribution of Oil.
Source: *Marine Environmental Research* 11(2): 111-136.
Oil type/Oiling condition: Crude oil; light oiling
Relevance/pertinence to Injury Assessment: Moderate
Methods: This experimental study evaluated the short-term and long-term effects on infaunal activity following the application of North Slope crude (surface and buried oil) to the sand substrate, simulating a temporary stranding of an oil slick on an intertidal area.
Endpoints: Counts of burrow openings (mostly *Callianassa*)
Findings: Small amounts of North Slope crude oil introduced at low tide directly into burrow openings had limited and temporary effects on the number of burrow openings. Chemical analyses of cored samples showed small amounts of oil incorporated to a depth of 30 cm by the infaunal reworking of sediments. In contrast, a 1 cm layer of oil buried 5 cm below the sediment surface caused significant effects on the number of burrow openings the day after the beginning of the experiment (from 111 openings to nearly half). After a year, 20-30 new burrows were found within 20 cm of the margins of the experimental plot. These patterns continued even 2 years post-experiment. Bioturbation below the buried oil-saturated sand layer also declined dramatically, and the buried oil did not degrade significantly even after 2 years. The authors

further argued that the reduction in the number of burrow openings could be the result of several factors: mortality (buried oil only), area avoidance, and/or shift in burrowing activity.

Author: Conan *et al.* 1982
Title: The Long-Term Effects of the *Amoco Cadiz* Oil Spill [and Discussion].
Source: *Philosophical Transactions of the Royal Society of London. Series B. Biological Sciences* **297**(1087): 323-333
Oil type/Oiling condition: Crude oil; oiling conditions not reported
Relevance/pertinence to Injury Assessment: Moderate
Methods: This article reviewed of the overall effects of the *Amoco Cadiz* oil spill on intertidal and subtidal communities. Only descriptions regarding the effects on intertidal sand beach communities are summarized here.
Endpoints: N/A
Findings: During the first week after the spill heavy mortality was observed in intertidal and subtidal communities of low-energy sand shorelines. In the intertidal zone, most species of clams (Solenidae, Mactridae, Veneridae), the epipsammic crustaceans (Mysidaceae, Crangonidae), the heart urchin, and even the more resistant polychaete worms (*Nereis diversicolor*, *Arenicola marina,* and *Audouinia tentaculata*) were depleted. Population recovery following an oil spill will depend on the life history of each species affected. Variables to consider include: life cycle, fecundity and larvae dispersal ecology (planktonic vs. benthic). Species more likely to overcome the initial impact of an oil spill include those with high fecundity, short life cycles, and efficient dispersion via planktonic larvae. However, even species with similar life cycles can respond differently to the same stressor. One year after the spill, the clam species *Tellina fabula* did not show any signs of recruitment, *Donax vittatus* had an unstable recruitment, and *Tellina tenuis* a normal recruitment. One of these species, *T. fibula*, disappeared from the intertidal zone a few months after the spill, as its larvae failed to settle and survive. This analysis indicated that delayed effects on populations were experienced 2-3 years after the spill.

Author: De La Huz *et al.* 2005
Title: Biological Impacts of Oil Pollution and Cleaning in the Intertidal Zone of Exposed Sandy Beaches: Preliminary Study of the *Prestige* Oil Spill.
Source: *Estuarine, Coastal and Shelf Science* **65**(1-2): 19-29
Oil type/Oiling condition: Heavy fuel; light and heavy oiling
Relevance/pertinence to Injury Assessment: High
Methods: Seventeen exposed sand beaches were surveyed seven months after the spill, and compared to pre-spill data (1995-1996).
Endpoints: Species richness and abundance of six taxonomic groups (polychaetes, mollusks, marine crustaceans, semi-terrestrial crustaceans, insects, and others) along the beach profile (intertidal: swash, resurgence, retention; supratidal: dry sand) before and after the spill. Marine crustaceans are exclusive of the intertidal zone, while semi-terrestrial crustaceans are common on the upper tidal zone. The level of human disturbance was categorized based on cleanup effort: 1) no cleaning activity (beach apparently clean); 2) low cleaning activity (beach slightly oiled); 3) medium cleaning activity (beach moderately oiled); and 4) high cleaning activity (beach heavily oiled).
Findings: A decrease in the species richness was generally observed in all but one of the 17 beaches. Two mollusk species (*Donax trunculus* and *Angulus tenuis*) were not found after the

spill. Polychaetes, insects, semi-terrestrial crustaceans, and others lost species in all cases, with polychaetes losing the greater number of species (Figure C-1). The most affected beaches lost up to 66.7% of the total species richness after the spill. Most of the polychaetes were lost in the swash zone, and a decrease in insects and semi-terrestrial crustaceans was observed in dry sand. The dry sand zone received a high amount of oil and received intense grooming and cleaning, including the removal of the top centimeters of sand. This preliminary study suggested that community changes in the intertidal zone could not be explained by seasonal variations, pointing at the combined effect of oiling and cleanup activities.

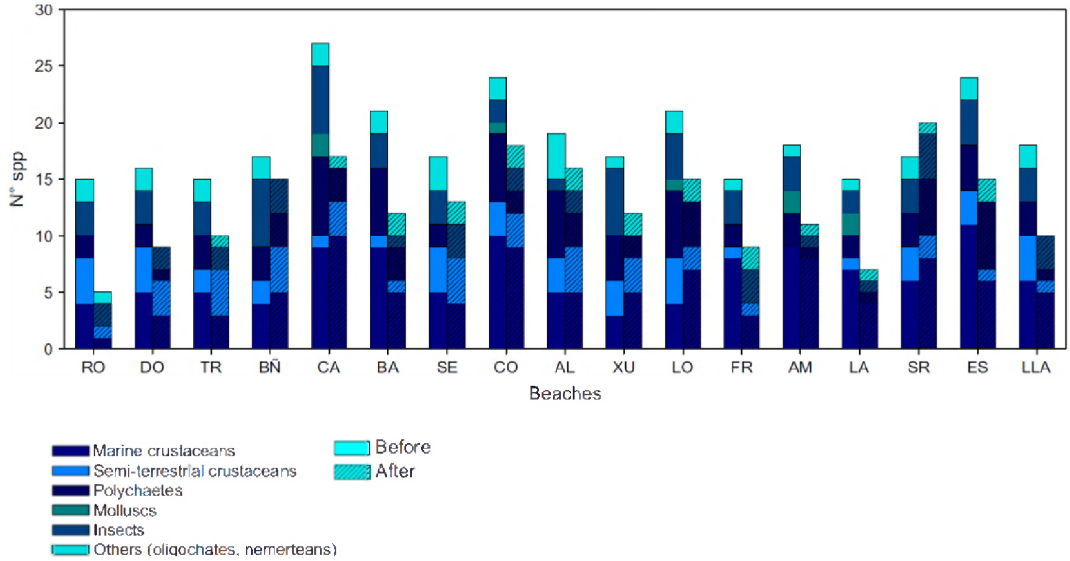

Figure C-1. Number of species in each macrofauna group before and after the oil spill. Cleanup effort was categorized as follows: 1) no cleaning activity: AM, SR, ES, LLA; 2) low cleaning: LA, FR; 3) medium cleaning: CO, XU, LO, DO; and 4) high cleaning: CA, RO, AL, TR, SE, BA, BN. Taken directly from De La Huz et al. (2005).

Author: Donaghy, L., H. K. Hong, H. J. Lee, J. C. Jun, Y. J. Park and K. S. Choi (2010).
Title: Hemocyte parameters of the Pacific oyster *Crassostrea gigas* a year after the *Hebei Spirit* oil spill off the west coast of Korea.
Source: *Helgoland Marine Research* **64**: 1-7.
Oil type/Oiling condition: Crude oil
Relevance/pertinence to Injury Assessment: Low to moderate
Methods: This study evaluated hemocyte parameters in *Crassostrea gigas* 13 months after the *Hebei Spirit* oil spill. Endpoints measured from field collected oysters included hemocyte concentration and mortality, relative proportion of hemocyte populations, phagocytosis and oxidative activity. Comparisons were mare relative to control specimens.
Findings/Summary: Hemocyte populations, phagocytosis and oxidative activity were depressed relative to controls, indicating compromised immunocompetence even a year after the spill. This study recommended continuing monitoring of oyster's immune capacities, as well as their resistance to disease.

Author: Felder and Griffis 1994

Title: Dominant Infaunal Communities at Risk in Shoreline Habitats: Burrowing Thalassinid Crustacea.

Source: OCS Study MMS 94-0007, US Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office, New Orleans, LA: 87

Oil type/Oiling condition: NA; NA

Relevance/pertinence to Injury Assessment: High

Methods: This study describes the biology and ecological roles of the estuarine (*Lepidophthalmus*) and beach ghost shrimp (*Callichirus*) in intertidal and shallow subtidal habitats of the Gulf of Mexico.

Endpoints: Density, distribution, biomass, growth and recruitment

Findings: This study provides detailed information on the density, distribution, biomass, growth and recruitment parameters in healthy ghost shrimp populations, which may be used as baseline information to characterize the impacts of oil on habitat, as well as indices of recovery. Brief descriptions of the findings are described below.

The estuarine ghost shrimp, *Lepidophthalmus louisianensis* is abundant in the intertidal zone of Bay St. Louis, Mississippi, and experiences seasonal and annual variations. Density, based on counts of surface burrow openings, can reach up 400 individuals/m^2 in the high and mid-intertidal zone, and lower (100-200 individuals/m^2) in lower intertidal zone. This species plays an important role in reworking the substrate where it inhabits, and oxygenating the sediment within a few centimeters of the burrow walls. At maximum densities of 400 burrows/m^2, this species constructs 9.33 m^2 of burrow surface, equivalent to 21.20 liters burrow volume/m^2 of sediment surface. At a mean density of 100 burrows/m^2 this species ejects approximately 1080 g wet sediment/m^2 day, or 4320 g wet sediment/m^2 day at its maximum density.

Beach ghost shrimp, *Callichirus islagrande*, is common on foreshore beaches, and is frequently found on both the gulf and bay beaches of barrier islands. The other beach ghost shrimp, *Callichirus major*, primarily inhabits bay side benthic habitats of barrier islands. Both species construct burrows in intertidal and shallow subtidal sediments. At Isles Dernieres, *C. islagrande* experience seasonal and annual variations, and are less dense in foreshore habitats (maximum density 90 individuals/m^2) than in bay habitats (maximum 750 individuals/m^2). Populations on the gulf shore side experience dramatically different density declines (i.e., 40 to 4 individuals/m^2) during periods of strong storm activity. This study also found that the gulf population shifts their distribution in order to maintain or regain their position in the lower intertidal zone relative to a moving beach crest. *C. islagrande* species play an important role in reworking the substrate where it inhabits, and oxygenating the sediment within a few centimeters of the burrow walls. At maximum densities of 220 burrows/m^2 this species constructs 5.25 m^2 of burrow surface, equivalent to 17.72 liters burrow volume/m^2 of sediment surface. At a mean density of 70 burrows/m^2 this species ejects approximately 3574 g wet sediment/m^2 day, or 11200 g wet sediment/m^2 day at its maximum density.

Although the impacts of oil and oil cleanup, followed by recovery times from injuries were not directly addressed, this report can provide the basis for assessing injury to the beach habitat. Information to consider includes: 1) burrowing depth, which commonly ranged from 40-200 cm in *L. louisianensis*, and 30-50 cm in *C. islagrande* and *L. sinuensis*; 2) species-specific densities; 3) their role in bioturbation and sediment reworking. This report indicated that the loss of burrowing shrimp populations from nearshore habitats resulting from physical or biological disturbances would decrease the rate of sediment turnover and nutrient flux.

Author: Fernández Méijome *et al.* 2006
Title: Assessing the Toxicity of Sandy Sediments Six Months after the *Prestige* Oil Spill by means of the Sea-Urchin Embryo-Larval Bioassay.
Source: *Thalassas* **22**(2): 45-50.
Oil type/Oiling condition: Heavy fuel oil; several degrees of oiling
Relevance/pertinence to Injury Assessment: Moderate
Methods: Six months after *Prestige* oil spill, the toxicity of sand collected from 10 exposed beaches impacted by the spill was tested by using the sea-urchin embryogenesis bioassay.
Endpoints: Embryo and larval length following a 48 h incubation period in sand elutriates
Findings: This study reported moderate toxicity (15% reduction in larval length) in sand elutriates collected from two of the ten sites. Although these two sites were heavily impacted by the spill, these sites also had the finest sands, and therefore, the effects on larval growth are not solely attributed to the residual fuel. Faster recoveries are expected in exposed beach habitats with strong hydrodynamic forces, and coarse sand sediments. These sites appeared to have recovered six months after the spill.

Author: Francioni, E., A. de L.R. Wagener, A. L. Scofield, M. H. Depledge and B. Cavalier (2007).
Title: Evaluation of the mussel *Perna perna* as a biomonitor of polycyclic aromatic hydrocarbon (PAH) exposure and effects.
Source: *Marine Pollution Bulletin* **54**(3): 329-338.
Oil type/Oiling condition: NA
Relevance/pertinence to Injury Assessment: Low to moderate
Methods: This study monitored the response of transplanted mussels (*Perna perna*) into oil contaminated sediments following a 3 month exposure period. Endpoints included tissue concentration of PAHs, and lysosomal stability.
Findings/Summary: The PAH concentration in mussels increased from ca. 100 μg/kg in newly transplanted mussels to 300 μg/kg following the 3 month exposure, while in mussels transplanted to the uncontaminated site PAH concentrations decreased by 75 % (from 380 to 80 μg/kg). Changes in lysosomal stability were noticed within one month of transposition, with neutral red retention times having a linear inverse correlation with PAH concentrations in tissues. Although these results may indicate mussel stress, other biological processes may have also contributed to the observed patterns (ovulation)

Author: Gelin *et al.* 2003
Title: Assessment of *Jessica* Oil Spill Impacts on Intertidal Invertebrate Communities.
Source: *Marine Pollution Bulletin* **46**(11): 1377-1384.
Oil type/Oiling condition: Diesel and bunker fuel; light
Relevance/pertinence to Injury Assessment: Low to Moderate
Methods: Surveys of intertidal invertebrate communities were conducted at impacted and reference sites 4-11 months post-spill.
Endpoints: Metrics of community structure included species abundance and species richness.
Findings: A total of 45 species were found, five of which were only present in reference sites. Species richness decreased with increased tide level, and in only one survey, this metric tended to be lower in impacted sites than in the paired-reference site. Generally, oiling effects were

much less than differences between sites and tidal heights, and therefore faunal relationships (species abundance, species richness, abundance of common taxa) did not show clear patterns related to oil exposure. This study did not find the disappearance in species, changes in community structure, or increased presence of dominant species.

Author: Grundy, M., M. Moore, S. Howell and N. Ratcliffe (1996).
Title: Phagocytic reduction and effects on lysosomal membranes by polycyclic aromatic hydrocarbons, in haemocytes of *Mytilus edulis*.
Source: *Aquatic Toxicology* **34**(4): 273-290.
Oil type/Oiling condition: NA
Relevance/pertinence to Injury Assessment: Low to moderate
Methods: This study evaluated the immune response of *Mytilus edulis* to *in-vitro* and *in-vivo* exposures to selected PAHs (phenanthrene, anthracene, fluoranthene). The main endpoint included phagocytosis and neutral red uptake and retention.
Findings/Summary: In *in-vitro* and *in-vivo* exposures, phenanthrene caused the greatest reduction in neutral red retention time, while anthracene had the least effects. While in the *in-vitro* exposures PAH combinations were more damaging than single treatments, whole animal exposures to single PAHs were more damaging than the PAH mixture. *In-vitro* and *in-vivo* exposures showed significantly depressed in haemocytes (reduced phagocytosis) when exposed to some PAH combinations. The study documented the link between PAHs exposures and sublethal adverse effect on cellular immune function.

Author: Grundy, M. M., N. A. Ratcliffe and M. N. Moore (1996).
Title: Immune inhibition in marine mussels by polycyclic aromatic hydrocarbons.
Source: *Marine Environmental Research* **42**(1-4): 187-190.
Oil type/Oiling condition: NA
Relevance/pertinence to Injury Assessment: Low to moderate
Methods: This study evaluated the immunological effects of PAHs (anthracene, fluoranthene and phenanthrene; 500 µg/L/day) in *Mytilus edulis* via *in vivo* exposures (2-4 weeks).
Findings/Summary: After a 2-week exposure, PAHs inhibited phagocytosis by 71% and damaged lysosomes by 69% compared to controls. In PAH contaminated areas lysosomal damage can compromise immune response to infectious diseases.

Author: Harty and McLachlan 1982
Title: Effects of Water-Soluble Fractions of Crude Oil and Dispersants on Nitrate Generation by Sandy Beach Microfauna.
Source: *Marine Pollution Bulletin* 13(8): 287-291.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Low to Moderate
Methods: This experimental work described the effects of oil (water-soluble fractions- WSF, dispersant- Chemserve OSE 750-, and oil/dispersant mixtures) on nitrate generation by beach microfauna.
Endpoints: Nitrate production rates
Findings: Significantly inhibited marine bacterial activity (nitrate production inhibited by 83% after 40 h) occurred even at the lowest WSF treatment (280 µg/L WSF). The WSF/dispersant mixture was toxic as it caused almost total inhibition within 20 h in even the 16-x dilution (6.25

%). Soluble pollutants associated with oil have drastic short-term effects on nitrate generation by beach microfauna. Based on the results from these experiments, the authors concluded that dispersants should not be used near beaches, because of the toxicity of the oil/dispersant mixture.

Author: Herrera-Bachiller *et al.* 2008
Title: The Ignored but Common Nemertine *Psammamphiporus elongatus* from the Galician Beaches (Spain), Affected by the *Prestige* Oil Spill.
Source: *Marine Ecology* **29**: 43-50.
Oil type/Oiling condition: Heavy fuel; light and heavy oiling
Relevance/pertinence to Injury Assessment: Low to Moderate
Methods: This study describes the morphology and ecology of a sand beach invertebrate, and includes a short description of the *Prestige* oil spill on this species.
Endpoints: N/A
Findings: *Psammamphiporus elongatus* was commonly found at the medium to low intertidal levels of sand beaches at densities ranging from 1.1 to 6.6 individuals/m^2. This species was not found in any of the five heavily oiled beaches nor in one lightly oiled beach in surveys one and two years post-spill. *P. elongatus* was likely eliminated from many beaches impacted by the spill, but has reappeared six and 18 months after the spill in 22% and 61%, respectively, of beaches sampled.

Author: Ingole *et al.* 2006
Title: Ecotoxicological Effect of Grounded *MV River Princess* on the Intertidal Benthic Organisms Off Goa.
Source: *Environment International* **32**(2): 284-291.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: Intertidal beaches nearby the grounding of the *MV River Princess* were assessed to quantify oil impacts on micro-, meio- and macrobenthos. Sediment samples were also collected and analyzed for dissolved Total Petroleum Hydrocarbon (TPHs).
Endpoints: Abundance, species richness, diversity, macrobenthos biomass, invertebrate ratios.
Findings: The microbenthos was comprised of microalgae, protozoans, and juvenile forms of meiobenthos. The site with the highest TPH value (89 µg/g) had a relatively low density of microbenthos (<10 individuals/3.3 cm^2), which were dominated by juvenile nematodes (87% of the total). The meiobenthic community was comprised of 13 taxa, with total densities ranging from 92 to 1057 individuals/10 cm^2. Nematodes were the dominant meiobenthic taxa ($\geq$ 60% of the total), followed by turbellarians and harpacticoid copepods. The macrobenthos were numerically dominated by polychaetes (8 species; 38% of the total) and crustaceans (7 species; 33% of the total), followed by a few species of bivalves. The polychaete/amphipod ratio and abundance-biomass comparison curves showed significant negative effects of TPH on macrofauna. Overall, the site with the highest reported TPH concentration appeared to negatively impact the abundance of meio- and macrobenthos.
Author: Junoy *et al.* 2005
Title: The Macroinfauna of the Galician Sandy Beaches (NW Spain) Affected by the *Prestige* Oil-Spill
Source: *Marine Pollution Bulletin* **50**(5): 526-536
Oil type/Oiling condition: Heavy fuel; light and heavy oiling

Relevance/pertinence to Injury Assessment: High
Methods: Six months after the *Prestige* oil spill, 18 sand beaches were surveyed to assess the impact of the fuel and clean-up activities on the macroinfauna community.
Endpoints: Before and after impact analysis of the diversity, richness, and species abundance of the macrofauna community
Findings: All of the beaches studied were in exposed environments and open to wave action. The number of species was higher in all beaches before the spill, and there was a negative relation between degree of oiling and species richness. Neither species diversity nor evenness was statistically significantly different before and after the spill, and there was not a clear correlation between these two indices and the degree of oiling. Macroinfauna abundance was generally lower after the spill compared to pre-spill levels. Prior to the spill, the macroinfauna community was numerically dominated by amphipods (*Pontocrates arenarius* and *Talitrus saltator*), isopods of the genus *Eurydice*, and polychaetes (*Scolelepis squamata*). Six months after the spill, the abundance of *Eurydic*e, *S. squamata*, nemerteans and larvae of Diptera species were significantly reduced, and their reduced abundances were related to the degree of oiling. Rare species (including mollusks) were completely eliminated. Changes in the macroinfauna community were attributed to the combined effects of oil and clean-up activities. No estimates of recovery were given.

Author: Kalpaxis, D., C. Theos, M. Xaplanteri, G. Dinos, A. Catsiki and M. Leotsinidis (2004).
Title: Biomonitoring of Gulf of Patras, *N. Peloponnesus*, Greece. Application of a biomarker suite including evaluation of translation efficiency in *Mytilus galloprovincialis* cells.
Source: *Environmental Research* **94**(2): 211-220.
Oil type: NA
Relevance/pertinence to Injury Assessment: Low
Methods: *Mytilus galloprovincialis* were exposed *in situ* to field waters from contaminated sites for a month, and digestive glands analyzed for lysosomal membrane stability, metallothionein content, and translational efficiency of ribosomes.
Findings/Summary: Mussels from contaminated sites showed a significant increase in lysosomal membrane permeability and metallothionein content, reduced polysome levels, and increased chromosomal damage compared to controls. These effects were attributed to metal exposures. This study highlighted the applicability of cellular markers as indicators of cellular stress response to contaminant exposure.

Author: Kennedy and Jacoby 1999
Title: Biological Indicators of Marine Environmental Health: Meiofauna–a Neglected Benthic Component?
Source: *Environmental Monitoring and Assessment* **54**(1): 47-68.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This paper discussed the use of meiofauna (45-500 μm in size) as indicators of marine environmental health. Some of the discussion presented here can be applied to the use of meiofauna in damage assessments.
Endpoints: N/A

Findings: The meiobenthos includes members of several taxa (Nematoda, Copepoda, Turbellaria, Gastrotricha, and Tardigrada), as well as temporary or immature members of larger phyla (Gastropoda, Holothuroidea, Nemertina, and Sipunculida). This group of minute organisms is among the most abundant known metazoan, and several attributes make them ideal for environmental monitoring: high species diversity, short generation time, benthic development, and tight association with the substrate throughout their life cycle, fast metabolic rates, and ubiquitous distribution. All these attributes translate into important ecological roles, and thus changes in meiofaunal populations can affect lower and higher trophic levels resulting in impacts on the perceived value of an ecosystem. An important characteristic that distinguishes meio from macrobenthos is their apparently lower sensitivity to mechanical disturbance and destabilization of sediments, and their higher confinement to the substrate which make them unable to disperse following an oil spill. Disadvantages to their use in monitoring include their small size, spatial and temporal variability, sample processing costs, and limited taxonomic literature. A summary of the disadvantages and advantages are presented in Table C-1.

Table C-1. Advantages and disadvantages of using meiofauna for environmental monitoring. Modified from Kennedy and Jacoby (1999).

Advantages	Disadvantages
Small size and high abundance indicate that small samples will contain enough total individuals for statistical tests	Small size makes counting and identifying meiofauna a difficult task
High species richness suggests that the information derived from sampling meiofaunal samples is high	Diversity and lack of taxonomic expertise hinders meiofaunal classification
Their ubiquitous distribution translates into high potential use as pollution indicators where macrofauna do not occur	Spatial and temporal variability of meiofaunal populations complicates distinction between natural and anthropogenic changes
Rapid generation time of meiofauna indicates that sublethal impacts may be detected more rapidly than in macrofauna	Resilience of meiofauna to impacts makes them less suitable indicators unless diversity metrics are considered
Direct benthic development and sessile habit indicates that meiofauna provide an integrated picture of impacts at a site	Extraction of meiofauna from samples is time-consuming and may lead to errors
Meiofauna are relatively sensitive to chemical pollution, but are relatively insensitive to physical disturbance, enabling the distinction between these two forms of stress	Their role in maintaining overall ecosystem integrity is not widely appreciated

Author: Krishnakumar, P., E. Casillas and U. Varanasi (1997).
Title: Cytochemical responses in the digestive tissue of *Mytilus edulis* complex exposed to microencapsulated PAHs or PCBs.
Source: *Comparative Biochemistry and Physiology. Part C: Comparative Pharmacology and Toxicology* **118**(1): 11-18.
Oil type: NA
Relevance/pertinence to Injury Assessment: Low to moderate

Methods: *Mytilus edulis* were fed a cocktail of PAHs (phenanthrene, fluoranthene and benzo[a]pyrene; 150 µg/L/day) and their digestive gland evaluated for lysosomal membrane stability and lipofuscin content.
Findings/Summary: Significant bioaccumulation of PAHs and alteration of several cellular markers were found following a 30 day exposure. Lysosomal membrane stability and gamma-glutamyl transpeptidase activity decreased following exposure, while lipofuscin content, NADPH-ferrihemoprotein reductase activity and neutral lipid content increased following exposure. These laboratory observations are comparable to the responses observed in field collected mussels. These results indicate that PAHs appear to be a contributing factor in the responses observed in mussels from habitats in Puget Sound.

Author: Laffon, B., T. Rábade, E. Pásaro and J. Méndez (2006).
Title: Monitoring of the impact of Prestige oil spill on *Mytilus galloprovincialis* from Galician coast.
Source: *Environment International* **32**(3): 342-348.
Oil type: Heavy crude oil
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study monitored the contamination caused by *Prestige* oil spill during an 11-month period by quantifying PAH concentrations in seawater, and tissues from *Mytilus galloprovincialis* collected from beaches impacted by the spill. DNA damage in mussel gills was assessed via comet assay. Recovery was also determined following a 7-day depuration period
Findings/Summary: PAH concentrations in water were generally below 200 ng/L, and DNA damage in oil-exposed mussels was significantly higher than in reference mussels. PAH concentrations showed a good correlation with DNA damage, and comet assay analysis indicated some DNA repair during the depuration period. These results indicated that the environmental impact of the *Prestige* oil spill persisted at least until June 2004.

Author: Li, Y., J. G. Qin, C. A. Abbott, X. Li and K. Benkendorff (2007).
Title: Synergistic impacts of heat shock and spawning on the physiology and immune health of *Crassostrea gigas*: an explanation for summer mortality in Pacific oysters.
Source: *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology* **293**(6): R2353.
Oil type: NA
Relevance/pertinence to Injury Assessment: Low
Methods: This study evaluated the interaction between spawning events and heat shock proteins in *Crassostrea gigas* under heat stress conditions (1-h 37 and 44 °C heat shock).
Findings/Summary: A single exposure to 44°C heat shock in pre- and post-spawning oysters induced mortality of all exposed organisms. Post-spawning oysters were less tolerant to heat shock than pre-spawning oysters. Levels of two heat shock proteins were low in gill tissues from post-spawning oysters after heat exposure indicating that spawning reduced heat shock protein synthesis. Spawning and heat combined reduced hemocyte phagocytosis and hemolymph antimicrobial activity in oysters indicating compromised immunocompetence.

Author: Long *et al.* 1987
Title: The Evolution of Stranded Oil within Sandy Beaches

Source: *1987 Oil Spill Conference*
Oil type/Oiling condition: Crude oil; heavy oiling
Relevance/pertinence to Injury Assessment: Low; may provide useful information on oil persistence.
Methods: Eight heavily oiled sand beaches were monitored over a three-year period after the *Amoco Cadiz* oil spill.
Endpoints: N/A
Findings: Despite massive cleanup efforts, all impacted beaches contained oil layers buried to various depths. These buried oil layers appeared to be mobile, and were believed to undertake downward migrations with each tidal cycle, particularly during the first six months post-deposition. Migration of hydrocarbons was driven by tidal-pumping and sediment porosity, and the persistence of oil depended on the geomorphological type of the beach. The residence time in a "transport beach system" (i.e., beaches with a thin sand layer) was possibly <1.5 years, and likely longer for "beach-dune system" beaches (i.e., beaches with a deep or thick sand layer).

Author: McLachlan and Harty 1982
Title: Effects of Crude Oil on the Supralittoral Meiofauna of a Sandy Beach
Source: *Marine Environmental Research* 7(1): 71-79.
Oil type/Oiling condition: Crude oil; several degrees of oiling
Relevance/pertinence to Injury Assessment: Moderate
Methods: Study of controlled oil spills with Arabian light crude on the meiofauna community associated with the supratidal zone of an exposed sand beach. Treatments included fresh oil, weathered oil, fresh oil dispersed with Chemserve OSE 750, and buried weathered oil.
Endpoints: Meiofauna composition and abundance
Findings: Meiofauna abundance at different depths (0- 20 cm) one month after exposures were lower at oil-sites (1,794-5,582 individuals) compared to controls (6,287 individuals). This decrease was most marked at the dispersed fresh oil plot (1,794 individuals), followed by the fresh and weathered oil plots (2,623 and 4,396 individuals), and the buried oil plot (5,582 individuals). These differences were attributed to oil toxicity and penetration. Five months post treatment meiofauna abundance did not differ between oiled plots and controls, except on the dispersed fresh oil plot (19% abundance below control levels). This recovery was primarily due to the increase in the abundance of nematodes, which were less sensitive to oil exposures. Oligochaetes, on the other hand, were the more sensitive group to oil exposures and their numbers did not recover to baseline levels within the study period. The density of harpacticoid copepods was generally low, and their sensitivity to oil exposures was not quantified. The authors concluded that oil deposited onto the surface of the substrate is more damaging to the meiofauna communities than oil deposited near the water table. Not surprisingly, fresh oil and dispersed fresh oil had more dramatic effects than weathered oil. This study concluded that the abundance of meiofauna recovered after 5 months of exposure, except under extreme oil exposures, though the community structure may take longer to recover (~1 year).

Author: Michel *et al.* 2008
Title: Bouchard B-120 Oil Spill Shoreline Injury Assessment: Injury Quantification, Buzzards Bay, Massachusetts and Rhode Island
Source: *Shoreline Assessment Team:* 195
Oil type/Oiling condition: Heavy fuel oil; very light to heavy oiling

Relevance/pertinence to Injury Assessment: High
Methods: This report summarizes the injuries associated with the intertidal oiling footprint following the *T/B Bouchard* oil spill. Only discussions pertaining to sand beaches (injury quantification and recovery) are presented here. Recovery rates were based on observations at oiled and reference sites, as well as the literature from previous spills and best professional judgment
Endpoints: NA
Findings: A summary of this report's assessment is presented in Table C-2. Several lines of evidence were used to characterize the recovery of beaches impacted by the *T/B Bouchard* oil spill. This report concluded that given the information available during the response and based on published literature, sand beaches would have recovered to baseline conditions 3.5 years after the spill.

Table C-2. Summary table of the estimated impacts to ecological services (recovery rates) for sand beaches oiled during the *T/B Bouchard* oil spill. Percentages are relative to pre-spill conditions.

Recovery attributes	Assessment descriptions
Injury category: Very Light Oiling	
Oiling distribution (extent; **acres**) and site descriptions	Minimal occurrence of oil: 1 tar ball/~10-15 ft **(4.12)**
Initial loss of service (**%**)	Cleanup efforts and wave action quickly returned these beaches to their pre-spill conditions. Amphipods and other macrofauna may have been affected by oil droplets stranded on the sand or contaminated wrack; localized injury **(90)**
Recovery at completion of cleanup (0.25 years; **%**)	Residual oil was cleaned naturally; substrates were likely suitable meio- and macrofauna; the short life cycle of amphipods (<1 yr) and some other macrofauna would have contributed to the recovery **(100)**
Injury category: Light Oiling	
Oiling distribution (extent; **acres**) and site descriptions	Drops/patches of oil were more frequent than at very lightly oiled areas; oil was found in wider bands and at higher cover; 5 months post-spill no oil was observed and amphipods would have been abundant within wrack **(11.4)**
Initial loss of service (**%**)	Oil and cleanup activities partially removed food resources (wrack, amphipods, shore crabs) **(50)**
Recovery at completion of cleanup (0.25 years; **%**)	Clean wrack likely re-deposited on the beaches, and the cleaned substrate was beginning to be suitable for colonization by meio- and macrofauna; the shoreline was manually disturbed, therefore the return of services was fairly quick **(70)**
Services 0.5 years post spill (**%**)	No oil was observed; accumulations of wrack appeared normal, and amphipods within the wrack would have been abundant; the buildup of wrack and increased abundance of macroinvertebrates would support the return of shorebirds **(90)**
Services 1.5 years post spill (**%**)	No oil remained on the beaches; wrack would have increased in size; species with short life cycles (<2-3 years) likely repopulated the area **(100)**
Injury category: Moderate Oiling	

Table C-2. Continued.

Recovery attributes	Assessment descriptions
Oiling distribution (extent; **acres**) and site descriptions	Oil mats or patties stranded along the beach covered 1-90% of the oiled area (**2.96**)
Initial loss of service (**%**)	Some beaches may have had potentially toxic levels of oil immediately after the spill; epifauna and infauna may have been stranded, smothered and killed by oil; wrack and associated invertebrate community were removed during cleanup; the presence of cleanup workers may have prevented the use of beach by fauna (**0**)
Recovery at completion of cleanup (0.25 years; **%**)	Some clean wrack would have been re-deposited on the beaches; cleaned substrate was beginning to be suitable for colonization (**5**)
Services 0.5 years post spill (**%**)	Wrack accumulations contained abundant amphipods; invertebrate populations were likely still recovering, therefore food quantity would have been low relative to baseline (**40**)
Services 1.5 years post spill (**%**)	No oil remained on the beaches; wrack deposits likely increased; invertebrate communities should have been near baseline; species with longer life spans (3-5 yrs) would likely be depleted relative to baseline (**90**)
Services 2.5 years post spill (**%**)	Species with long life cycles would continue to recover (**95**)
Services 3.5 years post spill (**%**)	Wrack accumulations should be normal; species with longer life cycles likely repopulated the area; epifauna and infauna should be fully recovered after 3 growing seasons (**100**)
Injury category: Heavy Oiling	
Oiling distribution (extent; **acres**) and site descriptions	Severe coating of oil; thick mats and patties of oil stranded on the beach; cleanup consisted mostly of manual removal of oiled sediments and wrack; 6 months post-spill no oil was observed, but buried oil was found at two sites (**6.63**)
Initial loss of service (**%**)	Some beaches may have had potentially toxic levels of oil immediately after the spill; epifauna and infauna may have been stranded, smothered and killed by oil; wrack and associated invertebrate community were removed during cleanup; the presence of cleanup workers may have prevented the use of beach by fauna (**0**)
Recovery at completion of cleanup (0.25 years; **%**)	Intense cleanup would have interfered with habitat use, and removal of oiled sediment and wrack would have removed all associated fauna; some buried oil was still present, which would further delay recovery (**0**)

Table C-2. Continued.

Recovery attributes	Assessment descriptions
Services 0.5 years post spill (%)	No oil was observed, and wrack accumulations contained abundant amphipods; buried oil was found; macroinvertebrates were likely still recovering, therefore food quantity would have been low relative to baseline; the buildup of wrack and cleaned substrate would begin to support invertebrate colonization, but the buried oil would have contaminated sand below the surface where infauna reside; higher loss of services as compared to the moderately oiled sand beaches **(30)**
Services 1.5 years post spill (%)	No oil was observed on the surface and buried oil had been removed; wrack was re-deposited and most epifauna and infauna would have re-colonized the area **(80)**
Services 2.5 years post spill (%)	Species with long life cycles would not have returned to pre-spill distributions **(90)**
Services 3.5 years post spill (%)	Under the assumption of similar natural recruitment rates compared to moderately oiled beaches, full recovery of services was estimated to occur by the end of the fourth growing season **(100)**

Author: Moore 2006

Title: State of the Marine Environment in SW Wales, 10 Years after the Sea Empress Oil Spill. A Report to the Countryside Council for Wales from Coastal Assessment, Liaison and Monitoring.

Source: *CCW Marine Monitoring Reports*. Cosheston, Pembrokeshire 21: 30.

Oil type/Oiling condition: Crude oil; light to heavy oiling

Relevance/pertinence to Injury Assessment: Low to Moderate

Methods: This report summarizes the long-term effects and recovery of shoreline and coastal resources following the grounding of the *Sea Empress*. Only descriptions relevant to sand beaches are included here.

Endpoints: Summary of findings from monitoring studies.

Findings: Only a couple of populations of burrowing infauna (echinoderms *Echinocardium cordatum* and spiny cockle *Acanthocardia echinata*) did not fully recover after 10 years, though other factors may have contributed to their slow recovery. Although the spill negatively impacted the abundance of amphipods (*Ampelisca brevicornis*) and some mollusks (*Cerastoderma edule*), and promoted the increase of opportunistic polychaetes (*Capitella* spp.), most populations returned to pre-spill levels nearly a year after the spill, except at heavily impacted areas where recovery continued into the second year (see citation for details). Even after two years of the spill, the abundance of small crustaceans was still low compared to pre-spill levels. Intertidal communities on severely impacted sand shores, recovered rapidly and no tangible effects were seen five years after the spill. Impacts of the most aggressive clean-up operations on sand beaches were mostly undetectable within two to three years.

Author: Moore *et al.* 1997a

Title: The Impact of the *Sea Empress* Oil Spill on Sandy Shore Meiofauna of South West Wales.

Source: *CCW Sea Empress Report* No. 230: 79

Oil type/Oiling condition: Crude oil; light to heavy oiling

Relevance/pertinence to Injury Assessment: Low to Moderate

Methods: Twelve sand beaches, representing a broad range of oiling, were revisited nine months after the *Sea Empress* oil spill.

Endpoints: Abundance, diversity and composition of the meiofaunal communities of intertidal sand beaches, with emphasis on dominant taxa: nematodes and copepods.

Findings: The density of nematodes and copepods from the most heavily oiled beaches did not show marked reductions relative to clean sites. No changes in species composition were observed at the heavier oiled sites. This study found no evidences of major impacts on the meiofauna community nine months after the spill event. The authors indicated that the results of this study cannot be extrapolated to the entire intertidal area, as isolated pockets of buried oil may persist particularly on the upper shore. The authors also indicated that the effect of this oil spill on the meiofauna community might be expected to be of short duration for intertidal communities and of longer duration for subtidal communities.

Author: Pichaud, N., J. Pellerin, M. Fournier, S. Gauthier-Clerc, P. Rioux and E. Pelletier (2008).

Title: Oxidative stress and immunologic responses following a dietary exposure to PAHs in *Mya arenaria*.

Source: *Chemistry Central Journal* **2**(1): 23
Oil type: NA
Relevance/pertinence to Injury Assessment: Low to moderate
Methods: This study evaluated the dietary effects of PAHs on *Mya arenaria.* Endpoints included oxidative stress (catalase activity and malondialdehyde levels) and immune responses (haemocyte number, efficiency of phagocytosis and haemocyte activity).
Findings/Summary: Haemocyte counts were significantly reduced after 9 and 17 days of exposure, and phagocytosis was significantly inhibition after 2 and 9 days of exposure. These results suggest that the PAHs may interfere with the maturation and/or differentiation processes of haemocytes. Oxidative stress endpoints were not altered by exposures. Recovery was noted for all the immune endpoints at the end of the experiment.

Author: Rabalais and Flint 1983
Title: Ixtoc 1 Effects on Intertidal and Subtidal Infauna of South Texas Gulf Beaches.
Source: *Contributions In Marine Science* **26**: 23-35.
Oil type/Oiling condition: Crude oil; moderate oiling
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study evaluated the effect of a tar mat from the Ixtoc oil spill on beach infaunal communities. Core samples were taken at different stations and analyzed for infaunal invertebrates during three sampling events in 1980 (March, July, October). Only descriptions given for the two intertidal stations are summarized here.
Endpoints: Number of species and infaunal abundance.
Findings: Intertidal stations had the lowest species number and abundance during the first post-impact sampling (<1 species/m^2; <250 individuals/m^2) compared to the following sampling (3 species/m^2; ~2000- ~47000 individuals/m^2). The latter sampling period was dominated by the polychaete, *Scolelepis squamata*, which comprised 81-97% of the total abundance. The third sampling event had species number and abundance somewhat in between the previous samplings (1-2 species/m^2; 600-2700 individuals/m^2). The increase in infaunal abundances could have been the result of reduced exposure to the remaining toxic compounds within the mat by increased sand deposition over the mat.

Author: Regoli, F. (2000).
Title: Total oxyradical scavenging capacity (TOSC) in polluted and translocated mussels: a predictive biomarker of oxidative stress.
Source: *Aquatic Toxicology* **50**(4): 351-361.
Oil type: NA
Relevance/pertinence to Injury Assessment: Low to moderate
Methods: This study evaluated the relative efficiency in scavenging capacity of various forms of oxyradicals (via induction of total oxyradical scavenging capacity, TOSC) in the digestive gland of *Mytilus galloprovincialis* from polluted and control populations, and from specimens translocated from clean to polluted areas (8 week exposures). This study also evaluated the interaction between TOSC and neutral red retention time in lysosomes of circulating haemocytes.
Findings/Summary: Mussels from polluted areas appeared to be more susceptible to oxidative stress and had a significantly lower capability to neutralize the various species of oxyradicals. Translocated specimens also showed a reduced antioxidant capacity. A significant increased in

lysosomal destabilization was evident in haemocytes of translocated mussels, and a high correlation was found between reduced TOSC values and lower neutral red lysosomal retention time. These alterations may result in the impairment of the health condition and changes in the physiological condition of mussels.

Author: Sami, S., M. Faisal and R. J. Huggett (1992).
Title: Alterations in cytometric characteristics of hemocytes from the American oyster *Crassostrea virginica* exposed to a polycyclic aromatic hydrocarbon (PAH) contaminated environment.
Source: *Marine Biology* **113**(2): 247-252.
Oil type: NA
Relevance/pertinence to Injury Assessment: Low to moderate
Methods: This study evaluated the effects of PAHs on the cytrometric characteristics of haemocytes from field collected *Crassostrea virginica.* Endpoints included haemocytes size and volume.
Findings/Summary: This study found significantly smaller haemocytes, and a lower occurrence of larger volume haemocytes in oysters form contaminated sites compared to relatively unpolluted sites. These changes point at a reduction in the number of circulating haemocytes and inhibition of phagocytic activity following exposure to pollutants. These changes were reversible upon the cessation of exposure.

Author: Scarlett *et al.* 2007
Title: Method for Assessing the Chronic Toxicity of Marine and Estuarine Sediment-Associated Contaminants Using the Amphipod *Corophium volutator*.
Source: *Marine Environmental Research* **63**(5): 457-470
Oil type/Oiling condition: Crude oil; NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study presented a method for quantifying the chronic toxicity of contaminants associated with whole sediments to the estuarine amphipod *Corophium volutator*. This experiment used slightly weathered Alaskan North Slope crude oil, water-accommodated-fraction (WAF) and a chemically dispersed (Corexit 9527) WAF. Amphipods were exposed to water and sediment spiked oil, WAFs and chemically-dispersed WAF.
Endpoints: Amphipod survival and growth
Findings: Nominal oil concentrations in sediments were 110, 220, and 440 μg/g dw. Amphipods exposed to the lowest and highest concentrations had significantly lower growth rates than controls, and the growth rates of survivors from the chemically dispersed WAF were lower (19 μg/day) than that seen in amphipods exposed to the Corexit (41 μg/day) and WAF (36 μg/day) treatments. Amphipod lengths followed the same patterns. At the end of the 75 d exposure period, the survival of amphipods exposed to the chemically dispersed WAF were much lower (23%) than the survival in all other treatments (>80%). Organisms exposed to oil spiked sediments (nominal concentrations 110 μg/g dw and 220 μg/g dw) and sediments spiked with chemically dispersed WAF had lower growth rates than that of control, Corexit and WAF treatments. Reproduction was observed in all treatments, although the some of the 220 μg/g dw and 440 μg/g dw chemically dispersed WAF treatment replicates did not have any offspring. All the chemically dispersed WAF treatment had significantly reduced reproduction rates than control, Corexit, and WAF treatments. This study indicated that, given the reproductive cycle of

this species, a spill occurring in early summer would have more severely impacted amphipod growth rates than if it occurred later in the year. In conclusion, sediment concentrations and toxicological response in the presence of the dispersant increased the concentration of bioavailable toxic components of the weathered oil, resulting in quantifiable effects on a sediment-dwelling organism.

Author: Schlacher *et al.* 2010
Title: Impacts of the *Pacific Adventurer* Oil Spill on the Macrobenthos of Subtropical Sandy Beaches.
Source: *Estuaries and Coasts*: 1-13.
Oil type/Oiling condition: Heavy fuel oil; heavy oiling
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study quantified changes to the benthic assemblage on a sand beach following the 270-t spill of heavy fuel oil from the *Pacific Adventurer* (13 km off Moreton Island, Eastern Australia). Beaches were sampled 1 week and 3 months post-spill, stratifying sampling along the beach face (lower, middle, upper shore).
Endpoints: Faunal density, species richness and diversity
Findings: Most of the oil deposited above the drift line on the middle and upper shore. One week after the spill, concentrations of heavy fuel oil in the sediment on the impacted areas ranged from 0.004 to 1.03 mg/g, and oil was not detected 3 months post-spill. A total of 35 species were found in sediment samples. The fauna composition was dominated by crustaceans (15 species; 77% of all individuals), followed by polychaetes (11 species; 18% of all individuals), molluscs (8 species; 3% of all individuals) and insects (1.4% of all individuals). One week after the spill the lower beach of the oiled sites had significantly lower total abundance and species density (30% and 10% lower, respectively; 54.1±8.3 individuals/ m^2) compared to reference sites (149.2±14.3 individuals/ m^2). The fauna on middle and upper shores were not different from reference sites. Three months post spill, the differences in fauna density and diversity between the lower shore of impacted and unimpacted beaches persisted, indicating a lack of short-term recovery. One week and three months post-spill the macrobenthic assemblage structure on the lower shore was different between oiled and unoiled beaches, due primarily to the reductions in the abundance of one polychaete (*Scolelepis* spp.) and three crustacean species, and secondarily to the increased density of 4 polychaete species at oiled sites. Although many variables may have contributed to the observed patterns, oil contamination was the most likely environmental variable explaining the observed ecological differences on the lower shore between impact and reference beaches. The author attributed these observed patterns to the presence of low molecular weight PAHs in the water, as well as to the percolation of oil on the upper shore and its dissolution in the water table. The authors concluded that despite the relatively small size of the spill, heavy fuel oil contamination can cause substantial impacts on sand beach ecosystems, and that recovery may be prolonged. Furthermore, this study documented effects despite the lack of visual detection of oil contamination.

Author: Schratzberger *et al.* 2003
Title: Response of Estuarine Meio-and Macrofauna to in Situ Bioremediation of Oil-Contaminated Sediment.
Source: *Marine Pollution Bulletin* **46**(4): 430-443.
Oil type/Oiling condition: Weathered crude oil; High

Relevance/pertinence to Injury Assessment: Low to Moderate
Methods: This study assessed the effects of weathered Forties oil and oil bioremediation on meio- and macrofauna found in sediment enclosures for 45 weeks post treatment in Stert Flats, Somerset, UK. Only descriptions regarding the unoiled/oil treatment are included here.
Endpoints: The benthic assemblage structure was quantified via Shannon-Wiener diversity, species richness and evenness. Nematodes were sorted based on their feeding strategy.
Findings: All oiled sediment enclosures showed a decreasing trend of total petroleum hydrocarbon (TPH) concentrations, from ~35000 µg/g post-treatment to ~7000 µg/g 45 weeks post-treatment. The nematode communities were generally more abundant (253±171 individuals per sample) and diverse (21±8 species per sample) than the macrofauna assemblage (abundance: 74±53 individuals per sample; diversity: 4±1 species per sample). Eleven weeks post treatment, mild effects of oil on benthic fauna were observed, including short-term shifts in dominance patterns, and absence of rare species in the oiled treatments. Decreased abundance of dominant nematode species in the oiled compared to unoiled sediments resulted in significantly higher evenness of benthic assemblages. There were no changes in the relative proportion of nematode feeding strategy across treatments. Forty-five weeks post-treatment, the nematode assemblage structure was similar between oiled and unoiled treatments. This study indicated that meiofauna (i.e., nematodes) were likely more sensitive to the effects of oil than macrofauna, primarily because meiobenthos are in direct contact with oil residues in the interstitial water.

Author: Strand *et al.* 1990
Title: Monitoring of Olympic National Park Beaches to Determine Fate and Effects of Spilled Bunker C Fuel Oil.
Source: *Report OCS/MMS-90-0061*
Oil type/Oiling condition: Bunker C; various degrees of oiling
Relevance/pertinence to Injury Assessment: Low to Moderate
Methods: A monitoring study (two surveys in 1989 and one 1990) was undertaken following the 1988 *Nestucca* oil spill of 230,000 gallons of Bunker C fuel oil onto Washington coastal beaches.
Endpoints: Hydrocarbon concentrations in sediment and in biological samples from intertidal fauna.
Findings: Relatively high concentrations of oil (6255 and 19,015 µg/g dry weight) were found in sediments during the second survey, and low concentrations 2 years after the spill (<250 µg/g). Concentrations of aromatic hydrocarbons found in mussels, clams, and other invertebrates were below 100 ng/g, with most below 45 ng/g. Relatively low concentrations of hydrocarbons in mollusk tissues collected from oiled beaches two years after the spill reflect a continuous exposure to residual oil buried within oiled beach sediments. This study suggested, based on low oil residues in sediment, that the long-term impacts on intertidal communities was likely not severe. The combination of a high-energy sand beach environment and the removal of oil mats and oiled debris during clean-up operations greatly reduced the level of residual oil contamination on beaches.

Author: Thebeau *et al.* 1981
Title: Effects of the Ixtoc I Oil Spill on the Intertidal and Subtidal Infaunal Populations Along Lower Texas Coast Barrier Island Beaches
Source: *1981 Oil Spill Conference*

Oil type/Oiling condition: Crude oil; oiling conditions not reported
Relevance/pertinence to Injury Assessment: Moderate
Methods: Pre-spill and post-spill sampling of intertidal and subtidal infaunal populations along Texas coast sand beaches was conducted to determine the impact of the 1979 Ixtoc I oil spill
Endpoints: Population density and number of species
Findings: Pre-impact information on the intertidal and subtidal infauna communities was collected along Texas sand beaches, and compared to post-spill surveys (1 month after the spill). The community was dominated by mollusks (8 species), polychaetes (15 species), and crustaceans (21 species). Numerically abundant intertidal species included the polychaetes, *Scolepsis squamata* and *Lumbrineris impatiens*, the bivalves *Donax* spp., the mole crab *Emerita benedicti*, and the haustoriid amphipod *Haustorius* spp. The intertidal community showed a decrease in total population densities between pre- and post-spill sampling periods, though not statistically significant. The number of species did not show significant changes between the two surveys. Population density changes may have been caused by factors other than the oil (i.e., beach erosion, beach cleanup) or by a combination of factors.

Author: Toro, B., J. M. Navarro and H. Palma-Fleming (2003)
Title: Relationship between bioenergetics responses and organic pollutants in the giant mussel, *Choromytilus chorus* (Mollusca: Mytilidae).
Source: *Aquatic Toxicology* **63**(3): 257-269.
Oil type: NA
Relevance/pertinence to Injury Assessment: Low to moderate
Methods: This study evaluated several biological activities (clearance rate, absorption efficiency, and oxygen consumption) and tissue concentrations (PAHs and oganochlorines, OC) in *Choromytilus chorus* collected at three sites with varying degrees of pollution. Scope for growth (SFG) was used to assess the physiological conditions of mussels.
Findings/Summary: Mussels from the highly polluted side showed negative SFG values (spring (-4.6 J/h per g; summer -3.5 J/h per g) indicating severe stress. These mussels also had lower clearance rates during spring, lower absorption efficiencies during both seasons, and much higher levels of PAHs and OCs than tissues from the other two sites. Mussels form the sites with medium and low level of pollution had positive SFG (>6.2 J/h per g). There was a significant negative correlation between the SFG and tissue concentrations of OCs and PAHs. Negative SFG energy and alteration of the energy balance may result in increased susceptible to diseases, predation and parasites.

Author: Tremblay, R., B. Myrand and H. Guderley (1998).
Title: Temporal variation of lysosomal capacities in relation to susceptibility of mussels, *Mytilus edulis*, to summer mortality.
Source: *Marine Biology* **132**(4): 641-649.
Oil type: NA
Relevance/pertinence to Injury Assessment: Low
Methods: This study evaluated the temporal variation of lysosomal activities and lysosomal stability in two stocks of *Mytilus edulis* susceptible to different patterns of summer mortality.
Findings/Summary: Mussels from the stock with a higher susceptibility to summer mortality had increased lysosomal enzyme activity and membrane destabilization induced by high temperatures and reduced food quality, and accumulated less glycogen in the mantle (used for

gonadal development) than mussels from the more resistant stock. The opposite patterns were seen in mussels resistant to summer mortality: inverse correlation between lysosomal enzyme activities and glycogen content. High activities of lysosomes were observed during spawning periods (related to gametogenesis) as well as during periods of stressful conditions. Mass mortality of mussels is associated with elevated activities of lysosomes, indicating high tissue autophagy.

Author: USFW Service (pers. comm.)
Title: *Cosco Busan* Report. Appendix E HEA inputs justification
Source: *Cosco Busan* Oil Spill, Trustees
Oil type/Oiling condition: Medium grade fuel oil; very light to heavy oiling
Relevance/pertinence to Injury Assessment: High
Methods: This report summarizes the injuries associated with the intertidal oiling footprint (within the band of oiling on the intertidal zone) following the *Cosco Busan* oil spill. Only discussions pertaining to sand beaches (injury quantification and recovery) are presented here. Recovery rates were based on observations at oiled and reference sites as well as the literature from previous spills and best professional judgment
Endpoints: NA
Findings: A summary of this report's assessment is presented in Table C-3. Several lines of evidence were used to characterize the recovery of beaches impacted by the *Cosco Busan* oil spill. This report concluded that given the information available during the response and based on published literature, sand beaches would have recovered to baseline conditions 3 years after the spill.

Table C-3. Summary table of the estimated impacts to ecological services (recovery rates) for sand beaches oiled during the *Cosco Busan* oil spill. Percentages are relative to pre-spill conditions.

Recovery attributes	Assessment descriptions
Injury category: Very Light Oiling	
Oiling distribution and site descriptions	75% of the beaches had <1% oil cover; 25% had 1-10% oil cover; oil stranded on the beach face during falling tides
Initial loss of service (%)	Very light oiling would foul fauna and reduce the use of the beach habitat by fish, invertebrates, and wildlife **(80)**
Recovery at completion of cleanup (2 months; %)	Cleanup methods included manual removal of tarballs and oiled wrack; Dominant species on sand beaches include amphipods and flies (<1 year life span), Coleopteran beetles (2 year life span), isopods (*Excirolana*, 2-3 year life span), *Emerita* (<1 year life span); chronic exposure to oil would have continuing effects because of their feeding behaviors and association with beach wrack where oil also tends to accumulate **(80)**
Services 6 months post spill (%)	Recovery based on assumption that affected species have would have returned to pre-spill abundances **(100)**
Injury category: Light Oiling	
Oiling distribution and site descriptions	71% of the beaches had <1% oil cover; 18% had 1-10% oil cover; 11% had 10-50% oil cover; oil stranded on the beach face during falling tides
Initial loss of service (%)	Light oiling would foul fauna and reduce the use of the beach habitat by fish, invertebrates, and wildlife **(60)**
Recovery at completion of cleanup (2 months; %)	Cleanup methods included manual removal of tarballs and oiled wrack; storm resulted in beach re-oiling resulting in re-exposure of PAHs to fauna; monitoring data indicate no lag in wrack accumulations, however, invertebrate communities are altered following wrack removal; mussels adjacent to lightly oiled beaches had PAH tissue concentrations indicative of on-going exposure to oil **(60)**
Services 6 months post spill (%)	Recovery based on assumption that affected species have would have returned to pre-spill abundances **(100)**
Injury category: Moderate Oiling	
Oiling distribution and site descriptions	57% of the beaches had 1-10% oil cover; 43% had 11-50% oil cover; oil stranded on the beach face during falling tides
Initial loss of service (%)	Moderate oiling smothered/fouled fauna using the habitat, rendering it unsuitable for use by fish, invertebrates, and wildlife; interstitial invertebrate species in spill area severely affected because of heavily oiled wrack **(40)**

Table C-3. Continued.

Recovery attributes	Assessment descriptions
Recovery at completion of cleanup (2 months; **%**)	Cleanup methods included manual removal of oiled sand and wrack; extensive trenching and sediment relocation took place at one site; interstitial invertebrate species in the cleanup zone were severely affected because of wrack removal; chronic exposure to oil would have continuing effects on invertebrates because of their feeding behaviors and association with beach wrack where oil accumulated; storm resulted in beach re-oiling resulting in re-exposure of PAHs to fauna **(40)**
Services 6 months post spill (**%**)	Invertebrate community structures are altered following wrack removal more than 6 months after removal; tarball stranding and re-oiling occurred along the outer coast sand beaches; PAH concentrations in mussels returned to ambient levels **(80)**
Services 1 years post spill (**%**)	Recovery based on life histories of dominant species (1-3 years) **(90)**
Services 3 years post spill (**%**)	Recovery reflects the time to restore age class distributions (by recruitment and immigration) **(100)**
Injury category: Heavy Oiling	
Oiling distribution and site descriptions	93% of the beaches had 11-50% oil cover; 7% had >90% oil cover; oil stranded on the beach face during falling tides
Initial loss of service (**%**)	Heavy oiling smothered/fouled fauna using the habitat, rendering it unsuitable for use by fish, invertebrates, and wildlife; interstitial invertebrate species in spill area severely affected because of heavily oiled wrack **(0)**
Recovery at completion of cleanup (2 months; **%**)	Cleanup methods included manual removal of oiled sand and wrack; extensive trenching and sediment relocation took place at one site; interstitial invertebrate species in the cleanup zone were severely affected because of wrack removal; chronic exposure to oil would have continuing effects on invertebrates because of their feeding behaviors and association with beach wrack where oil accumulated; storm resulted in beach re-oiling resulting in re-exposure of PAHs to fauna **(0)**
Services 6 months post spill (**%**)	Invertebrate community structures are altered following wrack removal more than 6 months after removal; tarball stranding and re-oiling occurred along the outer coast sand beaches; PAH concentrations in mussel samples from adjacent to interior beaches returned to ambient levels (**50**)
Services 1 years post spill (**%**)	Recovery based on life histories of dominant species (1-3 years) **(90)**
Services 3 years post spill (**%**)	Recovery reflects the time to restore age class distributions (by recruitment and immigration) **(100)**

Author: Vanderhorst *et al.* 1980
Title: Recovery of Strait of Juan De Fuca Intertidal Habitat Following Experimental Contamination with Oil: Second Annual Report, Fall 1979-Winter 1980.
Source: EPA-600/7-80-140 US Environmental Protection Agency. Washington, D.C.: 89.
Oil type/Oiling condition: Crude oil; oiling conditions not reported, but assumed high
Relevance/pertinence to Injury Assessment: Moderate to High
Methods: This report described several experimental studies on the recovery of infauna and epifauna of the intertidal zone following exposures to substrate treated with Prudhoe Bay crude oil. Oiled and unoiled substrates were placed in experimental units, which were intentionally arrayed in the field to evaluate the effects that tide level, site, season, and substrate type had on substrate colonization by naturally occurring invertebrates.
Endpoints: Number of species by fauna groups (polychaetes, crustaceans, mollusks, other), and species group densities.
Findings: Nearly 50% of the total initial oil concentration (1,758 µg/L total Prudhoe Bay crude oil) was lost three months post substrate treatment, and retention of residual oil was related to the initial oil loading and tidal height. Based on the rate of loss observed between 3 and 15 months post-treatment, it was estimated that the total hydrocarbons would have reached background levels in 18.5 months. Fifteen months post-treatment of oil-treated sands had 70-97% of the number of species, but only 48-75% of the fauna abundance found in non-treated sands. The invertebrate community in oil-treated sands was largely dominated, in number of species and abundance, by polychaetes (27-28 species; 49564-94405 individuals/m^2), followed by crustaceans (12-15 species; 7103-9602 individuals/m^2). Full community recovery in oil-treated sands was estimated to occur at 31 months post treatment. In several experiments, detritivorous and herbivorous species experienced the most severe effects from exposure to oil. The density of invertebrates was strongly influenced by tidal height, substrate composition, and season, suggesting that field experiments need to consider these factors to adequately assess the effects of oil on invertebrates.

Author: Veiga *et al.* 2010
Title: Meiofauna Communities in Exposed Sandy Beaches on the Galician Coast (Nw Spain), Six Months after the *Prestige* Oil Spill: The Role of Polycyclic Aromatic Hydrocarbons (PAHs).
Source: *Scientia Marina* **74**(2).
Oil type/Oiling condition: Heavy fuel; several degrees of oiling
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study evaluated the effects of the *Prestige* oil spill on invertebrate communities of six sand beaches six months after the spill, and compared their PAH loadings (40 parent PAHs) and meiobenthos community metrics with those of three reference sites. This study was confined to the swash zone, an area of the beach that received low or no cleaning activities.
Endpoints: Meiobenthos community structure and abundance.
Findings: Twenty nine PAHs, including most of the 16 parent PAHs, were detected in sediments at concentrations above the detection limit. Total PAH concentration ranged from 339 to 9070 ppb, and many parent PAHs were above the effects range-low (ERL) and effects range-medium (ERM). The meiobenthic community was comprised of 14 taxa largely dominated by copepods and nematodes. Total meiofauna density ranged between 64±4 individuals/10 cm^2 and 2100±480 individuals/10 cm^2. This study suggested that differences in total meiobenthic and main taxon

density between impacted and reference beaches could be related to the spill. Nematode abundance was generally lower in impacted areas, and copepod abundance was significantly lower at four impacted sites. In contrast, gastrotrich density was significantly higher at two affected sites. Multidimensional scaling (MDS) ordination showed different groupings between reference sites and most impacted beaches based on meiofauna abundance. Different site groupings may be explained by beach morphodynamics and the degree of impacts. Inter-annual variability of sand beach meiofauna could have also played a role on the observed patterns. Concentration of 1,2-dimethylnaphthalene and 1-methylphenanthrene may be related to changes in the meiobenthos community structure and the low meiofauna density values in affected beaches. This study concluded that six months after the spill, exposed sand beaches contained several PAHs at concentrations that could negatively impact the benthic fauna.

Author: Wormald 1976
Title: Effects of a Spill of Marine Diesel Oil on the Meiofauna of a Sandy Beach at Picnic Bay, Hong Kong.
Source: *Environmental Pollution* 11(2): 117-130.
Oil type/Oiling condition: Heavy marine diesel oil; heavy oiling
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study reported the immediate effects and recovery of the meiofauna community following a diesel spill.
Endpoints: Meiofauna densities
Findings: Nematodes and harpacticoid copepods were almost completely destroyed and other meiofauna were not found within four days of the spill. Copepods were more severely affected than nematodes, which reappeared within one month of the spill, and recolonization of the intertidal zone by both groups did not occur until eight months after the spill. During the first seven months post-spill, the meiofauna was restricted to the top centimeter of sediment, but their increase in numbers caused an increased distribution which extended down to 10 cm. Decline in nematode and copepod densities over the monitoring period was caused by remobilization of buried oil into groundwater by strong rainstorm events. The presence of toxic aromatic fractions coupled with low oxygen levels probably controlled recovery rates of the meiofauna, which appears to have recovered 15 months after the spill.

D. Biological Effects from Response-Disturbances and Related Activities

D.1 Response Activity Impacts from Historical Literature

Note: See Appendix C for additional observations

Author: Borzone and Rosa 2009
Title: Impact of Oil Spill and Posterior Clean-up Activities on Wrack-Living Talitrid Amphipods on Estuarine Beaches.
Source: *Brazilian Journal of Oceanography* **57**: 315-323
Oil type/Oiling condition: Bunker fuel oil; unknown
Relevance/pertinence to Injury Assessment: Moderate
Methods: Samples were collected from six estuarine beaches in Paranaguá Bay, Brazil pre- and 30 and 120 days post-impact/cleanup to characterize the talitrid amphipod fauna associated with beach wrack. Data from reports on the level of cleanup operation at each site (number of days and personnel) were used as indirect metrics of the fuel and cleanup activities. Human impacts were categorized as follows: 1) small: two cleaners working for two weeks post impact; 2) medium: up to five cleaners working for five weeks post impact; and 3) high impact: more than five cleaners working for 15 weeks post impact.
Endpoints: Species composition and abundance of talitrid amphipods
Findings: Three species of talitrid amphipods were collected during this study: *Platorchestia monody* (51% of the total abundance), *Talorchestia tucurauna* (48% of the total abundance), and *Atlantorchestoidea brasiliensis* (1% of the total abundance). The occurrence of *P. monody* and *T. tucurauna* increased from 3 and 5 pre-impact beaches, respectively, to all six post-impact beaches. By contrast, *A. brasiliensis* was found in 3 pre-impact beaches, but disappeared from all beaches 4 months post-impact. Beaches with medium to high impact showed changes in the composition of talitrids with increased dominance of *P. monody*. Although no drastic changes in the abundance of talitrids were documented after the spill, changes in the community structure were likely the result of cleanup activities. This study indicated that short (1-3 month) manual cleanup of the oiled wrack resulted in the increased abundance of some talitrid species.

D2. Physical Disturbance

Author: Defeo *et al.* 2009
Title: Threats to Sandy Beach Ecosystems: A Review.
Source: *Estuarine, Coastal and Shelf Science* **81**(1): 1-12.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate.
Methods: This article reviewed the impacts associated with several anthropogenic pressures (including trampling and off-road vehicles, grooming, and beach nourishment) on sand beach habitats. Only observations relevant to this literature synthesis are included here.
Endpoints: NA; NA
Findings: Non-quantitative key points of this review on grooming and cleaning are summarized as follows (see citation for references and details): *Trampling and off-road vehicles*–1) macrobenthic populations and communities often respond negatively to increased human activity levels; 2) off-road vehicles can disturb, injure or kill beach fauna; 4) the implication of off-road vehicles effects on invertebrates at higher ecological levels is unknown; 3) some recovery may occur during periods of low activity (Figure D-1). *Grooming*–1) wrack removal has significant ecological consequences, including the reduction of important invertebrate prey for higher

trophic levels; 2) meiofauna communities may recover quickly (24 h) from a single, short-term grooming event, but the consequences of recurrent events are unknown; 3) the effects of grooming could be noticeable at scales ranging from weeks to years and from <1 to 100 km; 4) (Figure D-1). *Nourishment*–1) these activities can result in impacts at the population (demography and dynamics), community (species richness) and ecosystem (functional processes, nutrient flux, trophic dynamics) levels; 2) the nature and extent of ecological impacts are influenced by the mechanical processes and the timing of these projects; 3) the initial impacts on invertebrates include direct mortality via burial; 4) other impacts that may affect invertebrates include compaction, as it modifies the interstitial spaces, capillarity, water retention, permeability and the exchange of gases and nutrients; 5) effects may be compounded by changes on beach morphology; 6) flattened surfaces can be colonized by opportunistic macrofauna, reducing species diversity and the abundance of dominant species; 7) the effects are often short-term with recovery occurring within months (Figure D-1).

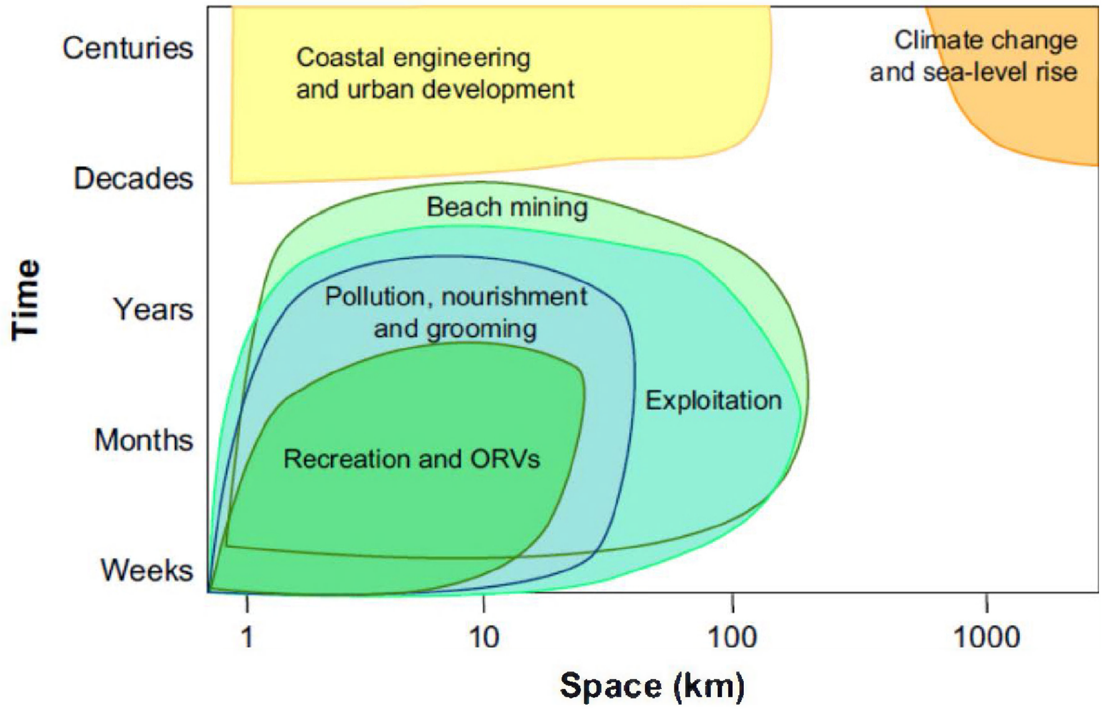

Figure D-1. Relative temporal extent of impacts as a function of the potential spatial extent of anthropogenic pressures on sand beach habitats. Source: Defeo et al. (2009).

Author: Weslawski *et al.* 2000b
Title: Sandy Coastlines-Are There Conflicts between Recreation and Natural Values?
Source: *Oceanological Studies* **29**(2): 5-18.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Low
Methods: This paper provides insight into the goods and services provided by sand beaches, as well as on the impacts of increased human activity on the biota inhabiting these areas.
Endpoints: N/A

Findings: Some of the main points of this review are the following (see original article for citations):

- Animals that occur in the intertidal zone have a relatively small area of distribution compared to subtidal fauna. For example, the beach-dwelling sandhopper (*Talitrus saltator*) occurs in a 2-5 km^2 area along a 500 km long sand beach shore compared to the closely related sand sublittoral crustacean *Bathyporeia pilosa*, which occurs in an area of 2000-3000 km^2 on the same coast.
- Trampling has been found to be responsible for the disappearance of sandhoppers from the most frequently visited beaches in Poland.
- Removal of wrack along with the removal of the upper layer of sand and sand sifting through a 5 mm sieve removes important food sources for key species, and it has also been linked to the disappearance of macrofauna (i.e., sandhoppers) and the decline of their predators.
- 3000 steps/m^2 day on a popular beach caused sufficient fragmentation, and mixed debris with sediment down to l0-30cm.

D2.1. Sediment Removal and Placement

Author: Bilodeau and Bourgeois 2004
Title: Impact of Beach Restoration on the Deep-Burrowing Ghost Shrimp, *Callichirus islagrande*.
Source: *Journal of Coastal Research* **20**(3): 931-936.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: High
Methods: This study characterized the impacts of a beach restoration project on the intertidal populations of the burrowing ghost shrimp over a 2.5 year period. Two barrier islands of the Isles Dernieres chain of Louisiana (East and Trinity Islands) where restoration took place were compared to reference islands within the chain.
Endpoints: Recolonization rates
Findings: Prior to the restoration on East Island, the ghost crab occurred in high population densities (30-100 burrows/m^2) along the intertidal sand substrate. Surveys during a 2.5 year period post restoration did not find large densities of this species, except for a few juveniles and an ovigerous female. This population did not show any signs of recolonization or recruitment at either of the two restored islands, a striking contrast to the generally well-established populations at 4 of the 5 reference islands. The lack of recolonization was attributed to changes in the sediment composition in the intertidal zone. Alteration of the substrate composition (i.e., high levels of silt and clay) appeared to be critical in ensuring successful settlement, burrowing, and persistence of this ecologically important macrobenthic species.
See: Felder and Griffis 1994

Author: Cobb and Arnold 2008
Title: Assessment of Nourishment Impacts to Beach Habitat Indicator Species in Pinellas County, Florida October 2005 - July 2007.
Source: *Final Report to the Florida Fish and Wildlife Conservation Commission*. St. Petersburg, Florida: 78.
Oil type/Oiling condition: NA; NA

Relevance/pertinence to Injury Assessment: Moderate to High
Methods: This study evaluated the effects of beach nourishment (Sand Key-Pinellas County, Florida) on several key beach-habitat indicator species: the ghost crab (*Ocypode quadrata*), the mole crab (*Emerita talpoida*), coquina clam (*Donax variabilis*), and polychaetes of the genus *Scolelepis*.
Endpoints: Comparison of temporal (before and after nourishment project) and spatial abundance (nourished and control areas) and size distributions of indicator species; ghost crab burrow density and size.
Findings: Beaches at Sand Key were widened by 61-129% by filling in 2006. At all sites, the distribution of indicator species was highly variable within the swash zone. Coquina clams (shell length 3.0-16.2 mm) exhibited high temporal and spatial variability, but were most abundant between October and November. The nourishment project had no lasting effects on the abundance of clams. By contrast, the abundance of the mole crab (carapace length 2.5-25.4 mm) was generally low, but peaked during July-November, and apparently experienced large impacts from the nourishment project, which coincided with the beginning of the recruitment period. Polychaetes, on the other hand, exhibited a high natural temporal and spatial variability, and apparently were not impacted by the project. Two of the three control sites had greater burrow densities, however, spatial variability was great and no conclusions were made regarding the effects of the project on this species. Overall, shifts in sediment composition and slope changes of the lower beach did not affect population densities of key indicator species.

Author: Irlandi and Arnold 2008
Title: Assessment of Nourishment Impacts to Beach Habitat Indicator Species.
Source: *Final Report to the Florida Fish and Wildlife Conservation Commission: 39.*
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate to High
Methods: This study evaluated the effects of beach nourishment (Sand Key-Pinellas County, and Indian River County, Florida) to important indicator species for beach habitat in Florida's Comprehensive Wildlife Conservation Strategy: the ghost crab (*Ocypode quadrata*), the mole crab (*Emerita talpoida*), and the coquina clam (*Donax* spp.).
Endpoints: Spatial and temporal patterns in the abundance of mole crab and coquina clam in the swash zone and the ghost crab along the upper beach of nourished and un-nourished beaches.
Findings: The abundance of mole crabs and coquina clams was highly variable in space and time resulting in no measurable impacts to these species from dune construction or nourishment projects on either coast. By contrast, these projects significantly reduced the burrow densities of ghost crab at impacted sites compared to control sites, possibly due to the disturbance caused by burial and/or bulldozing. Recovery of ghost crab populations did not occur after one year post project. In the case of the mole crab, timing rather than the location of nourishment activities appear to influence its abundance more strongly than that of other target species, and the abundance of the mole crab and the coquina clam appears to be negatively impacted by the slope of the swash zone. Grain size, organic content, amount of fine sediments, and amount of fill can play a key role in the assemblage of infauna, and changing these factors can affect the recovery of the infaunal community (i.e. a delayed recovery or colonization of a different assemblage). However, the initial shifts in sediment composition at Sand Key were not significant enough to affect population densities of key indicator species.

Author: Jones *et al.* 2008a
Title: The Effects of Beach Nourishment on the Sandy-Beach Amphipod *Exoediceros fossor*: Impact and Recovery in Botany Bay. New South Wales, Australia.
Source: *Marine Ecology* **29**: 28-36.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study evaluated the impacts of beach nourishment on the intertidal exoedicerotid amphipod, *Exoediceros fossor*. This study also evaluated impacts at the intertidal borrow/extraction site. Assessments were made via a Before-After, Control-Impact sampling design. The After sampling took place 9 weeks and ~44 weeks post-completion of the nourishment project.
Endpoints: Amphipod abundance, spatial variability, and recovery
Findings: At the nourishment site, erosion produced a vertical scarp causing the intertidal zone to be ~1 m lower than the supratidal zone. Amphipods were completely absent from the nourishment site following the completion of the project, but some recovery was seen 9 weeks later. Given the substantial pre-nourishment abundance of this amphipod, the impact of this project on this species was large. The elimination of this species was likely the result of death by burial or disturbance avoidance. The spatial variability between sampling periods within the nourishment site was not different from that of controls. At the burrow site, amphipods were completely absent post sand removal, but some degree of recovery was seen after 13 weeks at one of the sites. Removal of large volumes of intertidal sand reduced or eliminated the local population. Although recovery to baseline conditions did not occur during the sampling period, the authors indicated that recovery started within several weeks after the compaction of the project. Since this species does not have planktonic dispersing larvae, the recovery likely occurred through alongshore sediment drift that facilitated movement of adults or juveniles. Other factors that may have facilitated recovery include the year-round presence of adults and the continuous reproduction of this species. The authors concluded that the effects could have been much greater had the sediment composition of the receiving beach been different than the original substrate, and that large-scale operations are more detrimental to species that brood their young, to those with shallow burrows, and to species with seasonal reproductive cycles.

Author: Lindquist and Manning 2001
Title: Impacts of Beach Nourishment and Beach Scraping on Critical Habitat and Productivity of Surf Fishes.
Source: Final Report to the NC Fisheries Resource Grant Program, Morehead City: 107.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: High
Methods: This report describes the impacts of beach nourishment and mechanical redistribution of beach sand (bulldozing) on several resident beach organisms vital to the productivity of the beach and nearshore habitats. Only descriptions regarding effects on beach invertebrates are presented here.
Endpoints: Abundance of beach macroinvertebrates
Findings: Benthic sampling data showed no significant differences in the abundances of the dominant intertidal macroinvertebrate (i.e., coquina clams *Donax variabilis*, spionid polychaete *Scolelepis squamata*, and amphipod *Amphiporeia virginiana*) between bulldozed and control beaches. Although mole crabs (*Emerita talpoida*) showed reductions in abundance at the

bulldozed beach, these changes were not statistically significant from controls. By contrast, significant declines in abundance of the ghost crab (*Ocypode quadrata*) –not a dominant species on these beaches–occurred 6-8 months following beach bulldozing. This report indicated that: 1) lower abundance of ghost crab at bulldozed areas may indicate deliberate avoidance of these areas; 2) bulldozing during the winter season (mid-November to March), when crabs are permanently below ground, may have buried them causing direct mortality; 3) slow recolonization occurs via juvenile recruitment; 4) changes in the sand composition from bulldozing may impede the formation of stable burrow structures; and 5) complete recovery of ghost crabs on beaches that undergo repeated bulldozing each year is unlikely.

Several beach taxa were also negatively impacted by the disposal activities, with pronounced effects (reduced abundance) on coquina clams (*D. variabilis and Donax parvula*), mole crabs, ghost crabs and several species of amphipod (*Parahaustorius longimerus* and *Hausrorius* spp.). The lack of large individuals in the populations of mole crabs and clams at the disposal site suggests that, while these populations were recruiting, they either do not survive, experience reduced growth rates, or larger individuals suffer differential mortality. By contrast, *A. virginiana* did not show adverse effects from disposal activities.

The impact of large-scale beach disturbance activities (beach nourishment) on intertidal prey has the potential to translate into impacts at higher trophic levels.

Author: Nelson and Collins 1987
Title: Effects of Beach Renourishment on the Benthic Macrofauna and the Fishes of the Nearshore Zone at Sebastian Inlet State Recreation Area
Source: *Florida Institute of Technology*
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: High
Methods: This report describes the impacts of beach nourishment on several resident beach organisms at Sebastian Inlet, FL. Only descriptions regarding effects on beach invertebrates are presented here.
Endpoints: Number of species and abundance of macroinvertebrates in the wash zone
Findings: The mole crab (*Emerita talpoida*) and nemertean worms were the dominant invertebrates in all sampling sections. Other dominant invertebrates included archiannnelids, turbellarians, nematodes, oligochaetes, isopods, and calanoid copepods. There were no indications of a decrease in the number of species or a reduction in species abundance during the nourishment period (December 1985 - May 1986) or post-nourishment compared to pre-nourishment levels. Although there were changes in these measures of biological integrity, these reflect a high degree of natural variation likely resulting from a high spatial variability of the physical environment of the area. The nourishment project at Sebastian Inlet did not appear to have any measureable effect on indicator species.

Author: Peterson *et al.* 2000
Title: Short-Term Consequences of Nourishment and Bulldozing on the Dominant Large Invertebrates of a Sandy Beach.
Source: *Journal of Coastal Research* **16**(2): 368-378.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study evaluated the biological effects of dominant beach macro-invertebrates in Bogue Banks, North Carolina, to beach nourishment and bulldozing (beach scraping).

Endpoints: Intertidal macro-invertebrate density and active burrow counts
Findings: Beach nourishment changed the beach profile and slope, and altered the composition and characteristics of the substrate. Nourishment also caused dramatic changes in the density of two dominant species (mole crab *Emerita talpoida* and bivalve mollusks *Donax* spp.) compared to control beaches five to ten weeks post treatment. Mole crab densities declined from 137-159 individuals/m^2 on control beaches to 0-4 individuals/m^2 on nourished beaches, equivalent to a 99% decline. Similarly, *Donax* spp. densities declined from 264-334 individuals/m^2 on control beaches to 40-42 individuals/m^2 on nourished beaches, equivalent to an 86% decline. Nearly three months post bulldozing the topography resembled that of control beaches, but the overall beach width was shortened by 7 meters. Three months post bulldozing, active burrows of the ghost crabs *Ocypode quadrata* were on average 65% lower, and mole crab abundance was reduced by 37%. In contrast, *Donax* spp. abundance was five times that of control beaches. Changes in the composition of the substrate from nourishment may have impacted burrowing and abundance of the mole crab and other invertebrates. Similarly, bulldozing may have altered the beach morphology enough to reduce the habitat suitability for intertidal macro-invertebrates.

Author: Peterson *et al.* 2006
Title: Exploiting Beach Filling as an Unaffordable Experiment: Benthic Intertidal Impacts Propagating Upwards to Shorebirds.
Source: *Journal of Experimental Marine Biology and Ecology* **338**(2): 205-221.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study documented the impacts of a beach-filling (nourishment) project in North Carolina on the sand beach intertidal community. Benthic invertebrate sampling was conducted 3, 5, 7, 9, and 11 months post beach-filling initiation.
Endpoints: Density of dominant macroinfaunal (bivalve *Donax* spp., the mole crab *Emerita talpoida*, haustoriid amphipods, and polychaetes, mostly *Scolelepis squamata*), and ghost crab (*Ocypode quadrata*) densities
Findings: The benthic macroinfauna was notably different between nourished and control beaches after the beach filling, with a much higher abundance of *Donax* spp. and amphipods over several months on undisturbed control beaches (85% and 89%, respectively). The mole crab also displayed significantly lower abundances on filled beaches during the first post-fill sampling month, and remaining lower, but not significantly different from controls, several months post-fill. Polychaetes, on the other hand, were not affected by the project. Ghost crab burrow counts across the flat beach were twice as high on control beaches, and summertime recruitment of this species appeared inhibited on filled beaches. This study indicated that beach filling can induce mass mortality on macroinfauna, with recovery dependent on the potential for recolonization by reproduction and/or immigration. The alteration of the infaunal biomass and changes on beach characteristics influenced the foraging behavior of several shorebird species. This particular beach nourishment project resulted in a perturbation that exceeded biotic resistance, and degraded the trophic transfer function (based on a reduction of beach use by feeding shorebirds) at least one warm season.

Author: Rakocinski *et al.* 1996
Title: Responses by Macrobenthic Assemblages to Extensive Beach Restoration at Perdido Key, Florida, USA.

Source: *Journal of Coastal Research* **12**(1): 326-353
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study evaluated the biological effects of a 2-year extensive beach restoration project (beach and profile nourishment) on the macrobenthic community at Perdido Key, Florida.
Endpoints: Community structure, species richness, diversity and evenness, total density, and density of key indicator species
Findings: Natural variation in species diversity ranged from 6 to 32 taxa/0.125 m^2 and was similar to that found in post-nourishment transects (4-29 taxa/0.125 m^2). In contrast, natural variation in total density ranged from 880 to 16256 individuals/m^2, whereas total density ranged from 88 to 4952 individuals/m^2 among nourished transects. Species diversity and total density were not statistically significant between natural variability and post-nourishment transects, indicating a nearly complete recovery of the macrobenthos two years post-nourishment. Seasonal variability in diversity and evenness was observed between winter and summer (low and peak values, respectively), but it was consistent between natural variability and post-nourishment transects. Based on the description provided by the authors, most of the stations were subtidal and no further discussions are presented here.

Author: Reilly and Bellis 1983
Title: The Ecological Impact of Beach Nourishment with Dredged Materials on the Intertidal Zone at Bogue Banks, North Carolina
Source: *U.S. Army Corps of Engineers, Coastal Engineering Research Center, Miscellaneous Report*. 83.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study evaluated the effects of beach nourishment on an intertidal high-energy sand beach macrofaunal community. The nourished and comparison beaches were sampled before, during, and after nourishment. Before sampling established baseline quantitative data on the community structure and seasonal variation.
Endpoints: Indices of community structure: number of species, diversity, richness, equitability, dominance. Population patterns of indicator species.
Findings: This nourishment project involved the deposition of approximately 1.18 million cubic yards of dredged materials over a seven month period onto the beach at Fort Macon, NC.
Two species were relatively common along the high tide drift line: talitrid amphipods (*Talorchestia megalopthalma*) and the ghost crab (*Ocypode quadrata*). Ghost crabs were the most common higher order consumer above the swash zone except during winter when they remained dormant in their burrows. Overall, the density of ghost crabs was depressed following nourishment, with a summer population being nearly 50% lower than the pre-nourishment summer (280 crab burrows/km), likely due to emigration to other areas given the low densities of major prey species (*Donax* spp. and mole crab *Emerita talpoida*). During the first week of the nourishment project densities of the mole crab disappeared from the nourished zone, and remained absent for the duration of the project. A few weeks after the post-nourishment completion, juvenile mole crabs were found in the area indicating that increased sediment loading in the water column during the nourishment project prevented pelagic larval recruitment onto the intertidal zone. Similarly, the adult *Donax* population was completely eliminated from the nourished area likely by sediment smothering, and larval recruitment was inhibited by

changes in sediment characteristics. Adult and young *Donax* stages were absent during the first spring recruitment following beach nourishment, and did not recover even after 2 months of the completion of the project. The burrowing amphipod *Haustorius canadensis* was also completely eliminated, and their recovery was likely much slower than that of other infauna because they lack pelagic larvae. This species did not show signs of recovery during the post nourishment sampling period (2 months). Although invertebrate abundance declined over winter, the nourished area was completely voided of macrofauna species, and the recovery of this community likely required recruitment from nearby-unimpacted areas. The effects of nourishment are evident in all the community measures: low species diversity, richness and equitability were at their lowest values during the nourishment project compared to pre-nourishment levels, while only one species (mole crabs) was found during the duration of the project. Community recovery likely required one or two seasons following the project.

Author: Schoeman *et al.* 2000
Title: Lessons from a Disturbance Experiment in the Intertidal Zone of an Exposed Sandy Beach.
Source: *Estuarine, Coastal and Shelf Science* **50**(6): 869-884.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study evaluated the effects of a simulated disturbance (excavation and sand removal to a depth of 0.3 m) at Maitlands Beach, South Africa, on several invertebrate community metrics. This study included pre- and post-impact sampling at an experimental site and two control sites.
Endpoints: Species richness, macrofaunal abundance, and abundance and biomass of the dominant infaunal species, the beach clam *Donax serra*.
Findings: Some evidence linked changes in community structure to the experimental disturbance. Mean macrofaunal abundance were more different between impact and control sites than was the species richness. These impacts appeared to be temporary, with recoveries occurring within one semi-lunar cycle. At the disturbed site the abundance of *D. serra* differed from that of at least one of the control sites (before and after the disturbance), but these differences were not noted 16 days post disturbance. The biomass of *D. serra* also differed between the disturbed site and controls, but this metric was less sensitive to the disturbance than abundance. This study concluded that the macrobenthic community would require between 7 and 16 days to recover following a single disturbance event. Furthermore, species with poor horizontal locomotory ability may depend on tides and other forces to facilitate recovery.

D2.2. Beach Grooming and Wrack Removal

Author: Dugan *et al.* 2003
Title: The Response of Macrofauna Communities and Shorebirds to Macrophyte Wrack Subsidies on Exposed Sandy Beaches of Southern California.
Source: *Estuarine, Coastal and Shelf Science* **58**: 25-40
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study evaluated the role of macrophyte wrack subsidies on macrofauna abundance in 15 exposed sand beaches of which three were groomed regularly. Beaches were

categorized based on the level of wrack cover: high wrack cover (≥0.8 m^2/m), low wrack cover (<0.8 m^2/m), and groomed.
Endpoints: Community structure, and macrofauna species richness, abundance, and biomass.
Findings: On groomed beaches, the total cover of marine wrack was typically low (0.08 to 0.39 m^2/m), and covered <0.50% (range: 0.14-0.43%) of the beach. Abundant macrofauna on ungroomed beaches included talitrid amphipods (*Megalorchestia benedicti*, *Megalorchestia californiana*, *Megalorchestia columbiana*, and *Megalorchestia corniculata*), two isopod species (*Tylos punctatus* and *Alloniscus perconvexus*), and several coleoptera species (1-12 species) and beetles (~14 species), which comprised >37% of the macrofauna (range: 13.6-54.8%). Species richness and abundance, and biomass of wrack-associated fauna were significantly correlated with the standing crop of macrophyte wrack. Species richness of wrack-associated species on groomed beaches averaged <3 species, and were lower than those on low and high wrack cover beaches (>6 and >13 species, respectively). One of the groups most severely impacted by grooming was the Coleoptera, while talitrid amphipods were generally smaller in size and immature compared to ungroomed beaches. On average, abundance of wrack-associated macrofauna was nine times greater on ungroomed beaches with low wrack cover than on groomed beaches, and some of the lowest total macrofauna abundance were recorded on groomed beaches (<10,000 individuals/m). Overall, beach grooming had significant effects on the community structure (depressed species richness, abundance, and biomass) of wrack-associated macrofauna.

Author: Engelhard and Withers 1997
Title: Biological Effects of Mechanical Beach Raking in the Upper Intertidal Zone on Padre Island National Seashore, Texas.
Source: N. P. S. Padre Island National Seashore, Department of the Interior, Resource Management Division, Corpus Christi, Texas 50.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study documented the disturbance of the upper beach intertidal community from mechanical raking (0-3 cm penetration) for wrack removal at Padre Island National Seashore.
Endpoints: Species abundance and biomass in raked and unraked areas.
Findings: Sediment characteristics (total organic carbon, water content, chlorophyll *a*) were not significantly different between raked and unraked sites. Based on water content data, the temporal disturbance of the top centimeters through raking did not increase evaporation and desiccation of benthos. Benthic core samples produced a total of 9 taxa representing three groups: amphipods (78.9% of the total fauna), insects (12.4% of the total fauna), and polychaetes (8.7% of the total fauna). Amphipods were dominated by Haustorius spp. (77.2% of the total fauna) and *Orchestia grillus* (1.7% of the total fauna), while polychaetes were almost entirely comprised of *Scolelepis squamata* (99% of the total polychaetes). The macrofauna was clearly divided into benthic organisms (Haustorius spp. and polychaetes) and organisms associated with wrack (*O. grillus* and insects). The mean density and biomass of all macrofauna within three days post-raking, and the density and biomass *O. grillus* and polychaetes 7 and 10 days post-raking were significantly lower than in unraked areas. No significant differences were found 14 days post-raking. Macrofaunal density and biomass decreased as a result of direct removal during raking or due to vertical migration into the sand in response to the disturbance caused by raking. Haustoriid amphipods were likely unaffected because of their deep burrowing behavior

(optimal depth 5 cm; maximum depth 12 cm), while polychaetes and *O. grillus* may have been temporarily affected by direct mortality. Based on the results, it will take at least ten days for the recovery of macrofaunal populations from raking.

Author: Gheskiere *et al.* 2005
Title: Meiofauna as Descriptor of Tourism-Induced Changes at Sandy Beaches.
Source: *Marine Environmental Research* **60**(2): 245-265.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study evaluated the effects of tourism related activities on the sand beach meiofauna and nematofauna in the upper beach zone of two different coastal systems (Mediterranean and Baltic). Comparisons were made relative to pristine beaches.
Endpoints: Nematodes species abundance, diversity.
Findings: The two studied tourist sites are frequently cleaned with mechanical beach cleaners. At the two non-tourist sites percent total organic matter (%TOM) were higher in the upper beach zone consistent with the accumulation of marine and terrestrial detritus (range: 1.17-2.28%). In contrast, the tourist sites had concentrations of %TOM in the upper beach significantly lower (range: 0.25-0.34%) than the non-tourist beaches. %TOM concentrations were not statistically different in the middle and low intertidal zone between tourist and non-tourist beaches. Fourteen higher meiofauna groups were reported (in decreasing order of density): Nematoda, Turbellaria, Oligochaeta, Harpacticoida, Gastrotricha, naupliar larvae, Halacaroidea, Insecta, Amphipoda, Polychaeta, Tardigrada, Kinorhyncha, Gnathostomulida, and Acari. The upper beach fauna in tourist beaches was different from that of the middle and low beach, and had lower densities (particularly of the nematodes *Epsilonema pustulatum* and *Theristus heterospiculum*), lower diversities (absence of Insecta, Harpacticoida, Oligochaeta, terrestrial nematodes and marine Ironidae nematodes), lower number of distinctive taxa, lower genetic diversity (i.e., close taxonomic affinities), higher number of opportunist species, and higher community stress compared to non-tourist beaches. The upper beach community in tourist beaches also experienced complete replacement of species. Faunal differences between tourist and non-tourist beaches decreased towards the lower beach zones, and appeared to be more pronounced on the Mediterranean, possibly due to the length and intensity of the tourist period. Differences in meiofauna assemblage structure between the two beach types were primarily attributed to %TOM. This study demonstrated that mechanical cleaning of the tourist upper beaches had noticeable affects on the meiofauna and nematofauna.

Author: Gheskiere *et al.* 2006
Title: Are Strandline Meiofaunal Assemblages Affected by a Once-Only Mechanical Beach Cleaning? Experimental Findings.
Source: *Marine Environmental Research* **61**(3): 245-264.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study evaluated the impacts at a site on the Belgian coast of a 5 cm deep mechanical beach cleaning of man-made and natural wrack on strandline-associated meiofaunal assemblages, primarily on the free-living nematodes.
Endpoints: Meiofauna species abundance, taxonomic diversity, Pielou's evenness, and changes in community structure 24 hours after cleaning. Comparisons were made relative to control plots.

Findings: Thirteen meiofauna taxa were found in the freshly deposited strandline. Nematodes were the dominant taxa (69% of total; 55 species), followed by harpacticoid copepods and nauplii (14%), oligochaetes (10%), and turbellarids (4%). Significant changes in total abundance and community structure were observed between cleaned and control plots immediately after cleaning, with recoveries to initial levels following two high waters. Following mechanical cleaning the meiofauna abundance decreased from 338±41 individuals/10 cm^2 to 191±65 individuals/10 cm^2 (a 43% reduction), followed by a recovery with the first (261±48 individuals/10 cm^2) and second high waters (similar to initial levels). Differences in meiofaunal community structure were also observed between cleaned and control plots, with the highest dissimilarity occurring within the first 9 hours post cleanup. These changes were attributed to the reduced abundance of dominant nematode species (*Theristus otoplanobius*, *Trissonchulus benepapilosus*, *Chromadorina germanica*) and harpacticoid copepods. Recovery of the community structure was observed with the following high water. Impacts due to cleaning on species richness, Pielou's evenness, and taxonomic diversity were minor compared to daily fluctuations. Meiofauna are small metazoan animals with fast turnover rates, and may experience little responses to beach cleaning, as they can pass through cleaning sieves (30 mm). Although this study did not assess chronic impacts, turn-over rates are potentially important in maintaining long-term population levels. Deeper, more intense and repeated cleanings may result in much slower recolonization rates.

Author: Henry 1999
Title: Preliminary Investigations into the Possible Effects of Beach Scraping on Wooli Beach with Specific Reference to Intertidal Macroinfauna Diversity and Abundance.
Source: Bachelor of Science Thesis, School of Ecology and Environment, Deakin University, Warrnambool, Victoria.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This thesis evaluated the biological effects of beach scraping on the abundance of conspicuous sand beach invertebrates.
Endpoints: Species abundance
Findings: This work found significant differences in the abundance of bivalve *Donax deltoids* and the ghost crab *Ocypode cordimana* on a scraped beach compared to an untreated area. Although this study did not find differences in the abundance of other dominant species between the two sites, it documented generally lower vertical density and mean density of polychaetes on the scraped beach. Increased heavy pedestrian traffic could have also contributed to reduced abundance of important beach species.

Author: Malm *et al.* 2004
Title: Effects of Beach Cast Cleaning on Beach Quality, Microbial Food Web, and Littoral Macrofaunal Biodiversity.
Source: *Estuarine, Coastal and Shelf Science* **60**(2): 339-347.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Low to Moderate
Methods: This study evaluated the effects of beach cleaning of three recreationally important beaches in Sweden. These beaches encompass several cleanup intensities: 1) once a week; 2)

regularly when wrack accumulation occurs; and 3) regularly during the tourist season. In all cases, the sand was cleaned to a depth of 0.5 m with a tractor loader with a fork.
Endpoints: Water quality and pelagic and epifaunal communities associated with filamentous algal species. Metrics included biodiversity, abundance, and biomass.
Findings: This study documented significant changes in the organic content of sediments between un-cleaned and cleaned beaches, with much higher levels in un-cleaned beaches. Similarly, total animal biomass was significantly lower on the intensively cleaned beach compared with the un-cleaned beach, however, biodiversity and community structure were not significantly different between the two beach treatments. Bacterial production and large ciliate densities were higher on un-cleaned beaches, suggesting that the microbial food web benefits from the decomposing algal material. This study indicated that mechanical cleaning had noticeable effects on organic content, some effects on water quality and microbial production, and negligible effects on the macrofaunal biodiversity.

Author: Weslawski *et al.* 2000a
Title: The Sandhopper (*Talitrus saltator*, Montagu 1808) on the Polish Baltic Coast. Is It a Victim of Increased Tourism?
Source: *Oceanological Studies* **29**(1): 77-87.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Low
Methods: This study compared the distribution of the air breathing amphipods (a.k.a. sandhoppers) along 500 km of the Polish coastline and compared estimates to values reported in the 1950-1970s.
Endpoints: Occurrence of sandhoppers, human disturbance based on foot traffic.
Findings: Sandhoppers are generally more common in the supratidal zone (between the high water mark and the dunes) where they inhabit the upper 10 cm of sand. Sandhoppers were found in 44% of its initial distribution, and at lower densities (<20 individuals/m^2; range: 5-100 individuals/m^2) than surveys in the 1950-1970s (150 individuals/m^2). Sandhoppers completely disappeared from many beach sections along the shoreline. At many sites foot traffic disturbed the sediments from 5 cm down (1 step) to 30 cm down (100 steps). Human trampling and mechanical cleaning of sand beaches were presumed to have contributed to the declined occurrence of this species.

D2.3. Off-Road Vehicle Traffic

Author: Kluft and Ginsberg 2009
Title: The Effect of Off-Road Vehicles on Barrier Beach Invertebrates at Cape Cod and Fire Island National Seashores.
Source: Technical Report NPS/NER/NRTR-2009/138. National Park Service. Boston, MA
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This report describes the result of a study on the effects of off-road vehicles (ORVs) on invertebrates inhabiting wrack and supratidal sands on beaches of Massachusetts. Comparisons were made between wrack-laden beaches with and without vehicle traffic, and between experimental with and without traffic.

Endpoints: Faunal composition and invertebrate abundance.
Findings: Traffic-level at different sites ranged from 187 to 267 cars/day. Wrack was more abundant on beaches free of vehicle traffic (59% cover) than on beaches without traffic (42% cover), though overall invertebrate abundance in wrack/core samples was not different between areas open and closed to vehicles. Dominant taxa included oligochaetes, tethinid flies, talitrid amphipods, and coleopteran, encompassing a total of 79 species. Two species, the talitrid amphipod *Talorchestia longicornis* (beach hopper) and the wolf spider *Arctosa littoralis*, which are found at night along the beach with adults burrowing in the supratidal and juveniles concentrating under wrack, were less abundant on beaches open to vehicle traffic. These species were likely crushed in their burrows by daylight traffic. In contrast, other invertebrates (enchytraeid oligochaetes and tethinid flies *Tethina parvula*) found within/beneath wrack, did not respond to traffic disturbance. These interstitial detritivores showed a positive response (increased abundance) to vehicle disturbance possibly due to the increased moisture and mechanical breakdown of wrack by vehicle traffic. Experimental units with and without traffic indicated that the traffic disturbance can lower wrack invertebrate abundances proportionally to the traffic level. Vehicle traffic adversely affected beach invertebrates by direct mortality (crushing) and species displacement, by lowering the total amount of wrack (i.e., foraging and refuge habitat), and by lowering the abundance of wrack dwellers.

Author: Lucrezi and Schlacher 2010
Title: Impacts of Off-Road Vehicles (ORVs) on Burrow Architecture of Ghost Crabs (Genus *Ocypode*) on Sandy Beaches.
Source: *Environmental Management* **45**(6): 1352-1362.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study evaluated the effects of Off-Road Vehicles (ORVs) on the architecture of ghost crab burrows between beaches open and closed to traffic.
Endpoints: Shape and characteristics of burrow casts.
Findings: The sand at beaches impacted by traffic was slightly hotter and had a lower moisture content compared to beaches closed to traffic. The opening diameter of burrows on vehicle-impacted beaches tended to be smaller (30.8±1.1 mm) than on reference beaches (34.52±1.02 mm), indicating that smaller crabs were more common on vehicle -impacted beaches. On vehicle-impacted beaches crabs constructed much deeper (43.07 ±5.54 cm) and longer burrows, particularly during the peak traffic season, compared to reference beaches (30.67 ±2.33 cm). Ghost crabs may construct deeper burrows to avoid desiccation, and increased excavation effort may require higher energy expenditure at the cost of other important physiological processes (e.g., reproduction). Other ecological implications related to changes in the architecture of burrows were not discussed.

Author: Schlacher *et al.* 2007
Title: Vehicles versus Conservation of Invertebrates on Sandy Beaches: Mortalities Inflicted by Off-Road Vehicles on Ghost Crabs
Source: *Marine Ecology* **28**(3): 354-367
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate

Methods: This study quantified the effects of off-road vehicle (ORV) on ghost crabs (Ocypodidae; *Ocypode cordimanus* and *Ocypode ceratophthalma*).
Endpoints: Ghost crab abundance, burrow depth and mortality.
Findings: Crab densities were significantly higher in areas subjected to low to moderate beach traffic (range: 200-220 active burrow openings/30 m^2) compared to those with heavy beach traffic (115 active burrow openings/30 m^2). On low and moderate beach traffic areas, a larger percentage of the population was found living below the drift line (range: 6-7%) compared to heavy beach traffic areas (2%). In the most heavily impacted area, particularly on the upper shore closer to the foredune, ghost crabs were generally smaller indicating that the population shifted towards a larger proportion of juveniles. Although burrows partially protect crabs against cars, all individuals with shallow burrows (5 cm) were killed by $\geq$10 vehicle passes, compared to 10-30% mortality in ghost crabs with deeper burrows (20 cm). Most crabs with burrows of 30 cm (half of the population) were not killed by ORVs, and mortality declined exponentially with burrow depth. Nocturnal beach traffic appears to have larger effects on mortality than day light traffic, consistent with their night emergence onto the beach surface. This study explored several nocturnal traffic scenarios (see Figure D-2), and revealed that a single vehicle can crush up to 0.75% of the intertidal population, and that 100 cars would kill half of the intertidal ghost crab population. Furthermore, summer peaks in beach traffic overlap with the spawning period of ghost crabs, suggesting reduced recruitment to the population. Contributing factors to the decreased abundance in heavy traffic areas include reduced food availability, disruption of the physical properties of the sand substrate, large disruptions of the intertidal habitat (influencing recruitment), and continuous burrow maintenance increasing exposure to predators. This study concluded that ORVs can cause negative ecological consequences on sand beaches.

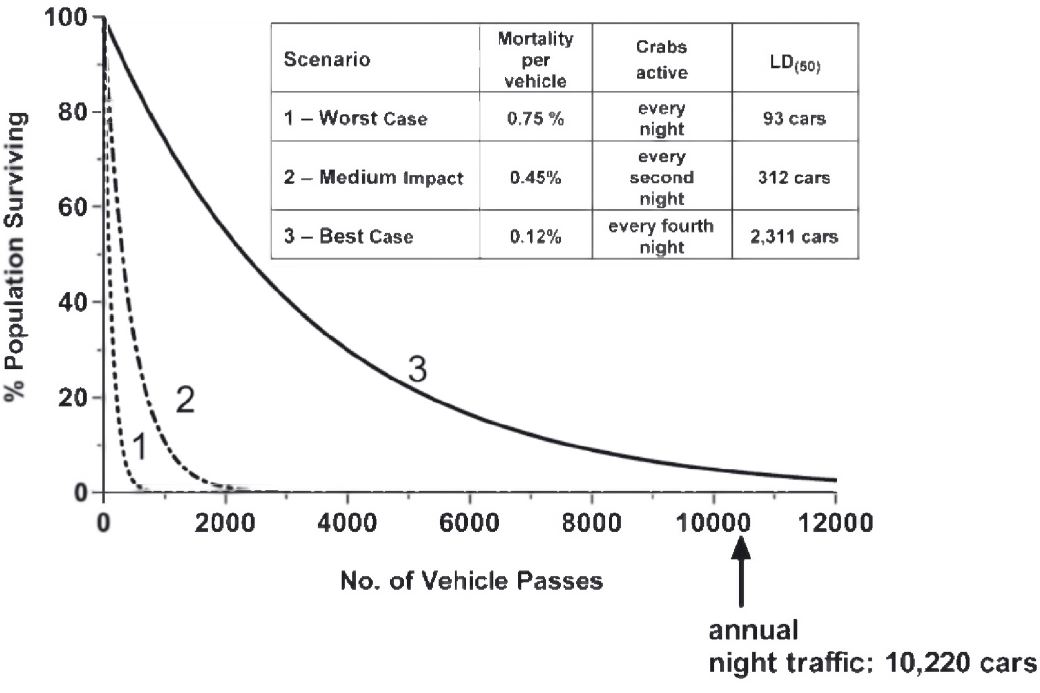

Figure D-2. Modeled declines in ghost crab populations as a result of direct mortalities caused by night-traffic. Scenarios are based on three levels of mortality recorded in this study, and different levels of crab activity. LD(50) denotes the numbers of cars predicted to reduce intertidal populations of ghost crabs by half. These modeled declines do not take into account recruitment, natural mortality and predation, or other human causes (i.e., daytime kills by ORVs). Taken from Schlacher *et al.* 2007.

Author: Schlacher *et al.* 2008
Title: Impacts of Off-Road Vehicles (ORVs) on Macrobenthic Assemblages on Sandy Beaches.
Source: *Environmental Management* **41**(6): 878-892.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study quantified the effects of off-road vehicle traffic on the intertidal beach invertebrate community in South-East Queensland, Australia, by comparing reference sites (no ORVs) and heavy traffic beaches (>250,000 vehicles/year).
Endpoints: Community composition, structure, species density and abundance.
Findings: There were no differences in sediment properties, beach morphology, and profiles between impacted and reference beaches. Beach traffic concentrated in the middle and upper sections of the beaches (74 vehicle passes/hour) compared to the lower beach (0-10 vehicle passes/hour). A total of 37 species were identified, with high dominance of polychaetes (15 species), followed by amphipods (6 species), bivalves (5 species), and isopods (4 species). Crustaceans were numerically more abundant (72.8% of all individuals). Some samples from the upper (84%) and middle (25-63%) impacted areas were defaunated compared to only 2-12% in reference samples. Less pronounced impacts were found in the lower zone. Impacted beaches also had significantly lower abundance, species richness, and diversity of macrobenthos. For example the middle zone supported only 34% of the total macrobenthos abundance of that from reference beaches (93 vs. 271 individuals/m^2), while densities on the upper zone were reduced by two orders of magnitude compared to reference sites (3.8 vs. 458.4 individuals/m^2). Shifts in community structure were primarily driven by the low abundances of the cirolanid isopod *Pseudolana concinna* (0.97 individuals/m^2) on impacted beaches compared to reference sites (435 individuals/m^2). This study concluded that vehicle traffic has significant effects upon the beach community resulting from direct crushing. The severity of the effects appears to depend on the compactness of the sand, species fragility (soft vs. hard bodies), and the depth of their burrows. Seasonal recovery in these communities is unlikely given the traffic volume and frequency.

Author: Schlacher *et al.* 2011
Title: Vegetation and Ghost Crabs in Coastal Dunes as Indicators of Putative Stressors from Tourism.
Source: *Ecological Indicators* **11**(2): 284-294.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study evaluated the effects of human disturbances (camping, vehicle traffic, trampling) on the ghost crab (*Ocypode cordimana*), and the relationship between beach habitat attributes and ghost crab abundance.
Endpoints: Ghost crab abundance, distribution, body size, and body condition.

Findings: The most widespread physical impact on ghost crab populations associated with camping was human trampling, but significant impacts are only likely in areas with intense human use. Ghost crabs were attracted to camping sites where food scraps are available as reflected in the higher values of the body condition index in individuals from nearby camping areas. This study did not find a strong correlation between crab density and beach attributes (i.e., physical habitat dimensions, the surface cover of vegetation, species diversity, or litter cover).

Author: Van Der Merwe 1991
Title: Effects of Off-Road Vehicles on the Macrofauna of a Sandy Beach.
Source: *South African Journal of Science* **87**(5): 210-213.
Oil type/Oiling condition: NA; NA
Relevance/pertinence to Injury Assessment: Moderate
Methods: This study documented the effects of off-road vehicles in South Africa on four intertidal macrofaunal species (gastropod *Bullia rhodostoma*, two bivalves *Donax serra* and *D. sordidus*, and a benthic mysid *Gastrosaccus psammodytes*), and one supralittoral species (isopod *Tylos capensis*).
Endpoints: Count of dead, injured, and uninjured organisms 24-hours post off-road activity (low and high intensity).
Findings: Percent damage of >25 mm and <20 mm *B. rhodostoma* was 0.9% and 12.3%, respectively, after low intensity (5 passes), and 0.6% and 3.1% respectively, after high intensity traffic (50 passes). Under the high intensity traffic treatment, the mean percentage of damaged *D. serra* was 7.4% for large individuals and 6.3% for small individuals, while for *D. sordidus* the overall damage was 2.9%. No significant differences between treatments were found for *Gastrosaccus* and no animals were damaged. The gastropod species was the most resistant, while the others were easily crushed. This study concluded that these four intertidal species were not dramatically impacted by vehicles, as long as they were buried and the sand was relatively compact. *T. capensis* was highly susceptible to vehicle impacts as the numbers of individuals crushed or damaged increased as a function of the number of vehicle passes, though the response did not change between small and large specimens. This isopod species was the most vulnerable to traffic because of its soft exoskeleton, high occurrence in soft, non-compacted sand, and high foraging activity, primarily at night, on the surface of the substrate.